ECCO2-Darwin:
A global, eddying biogeochemical ocean model for the NASA Carbon Monitoring System (CMS) Flux Project

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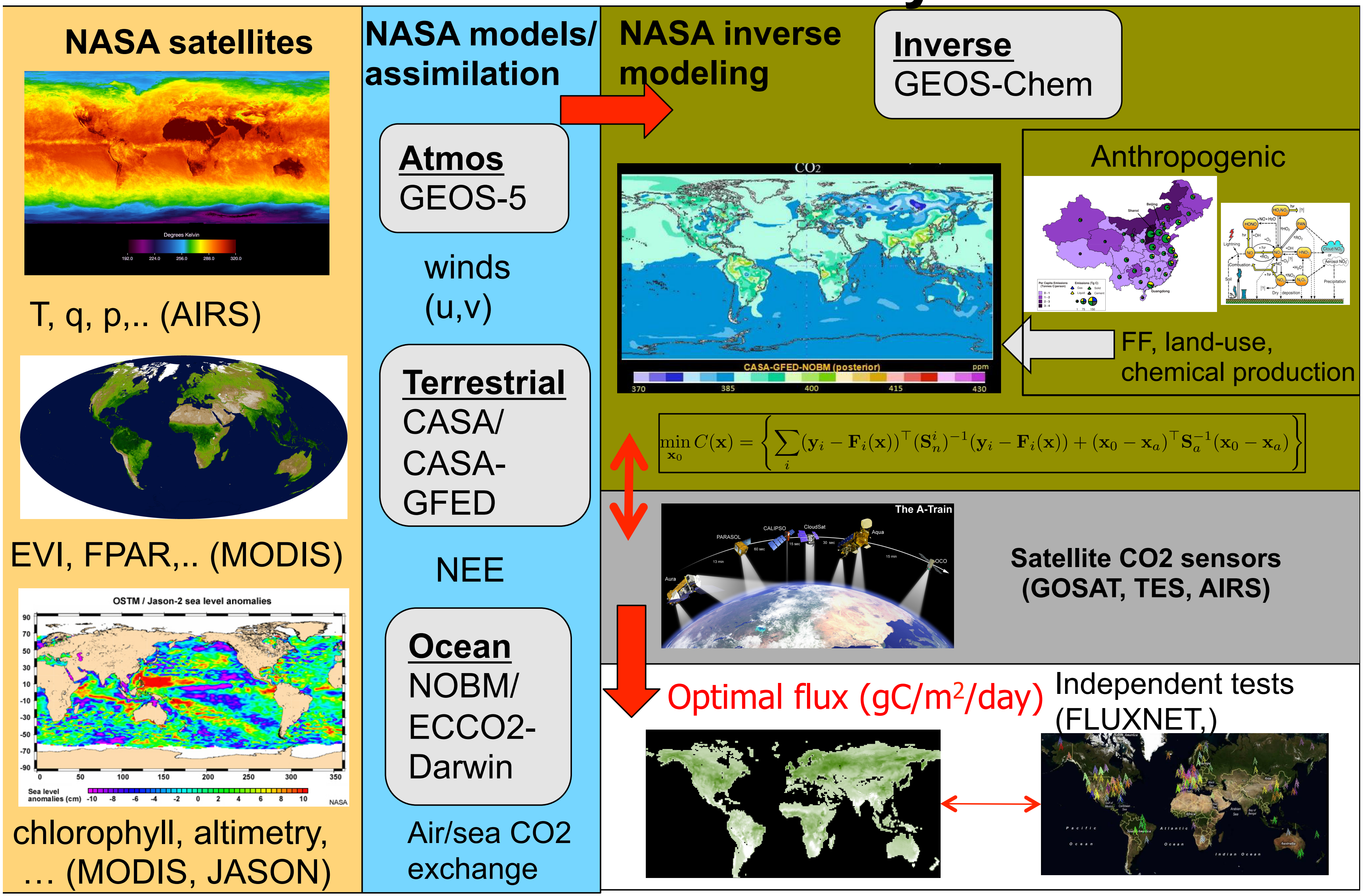
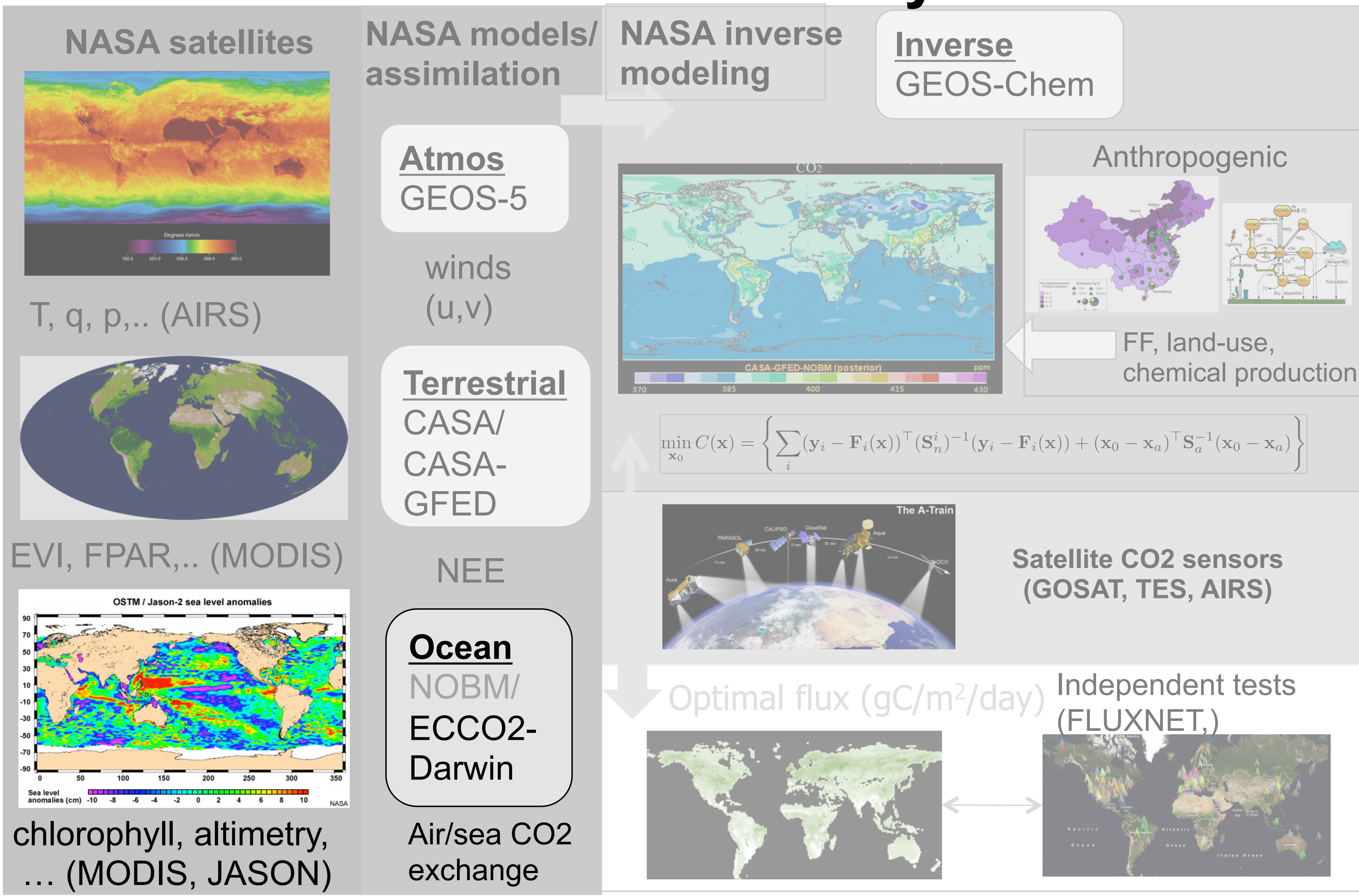
Outline

- What is CMS?
- Why do the oceans matter?
- How does the oceanic carbon system work?
- ECCO2 and biogeochemistry modeling
  - Merging two models
  - Initial calculations
  - Optimizing results

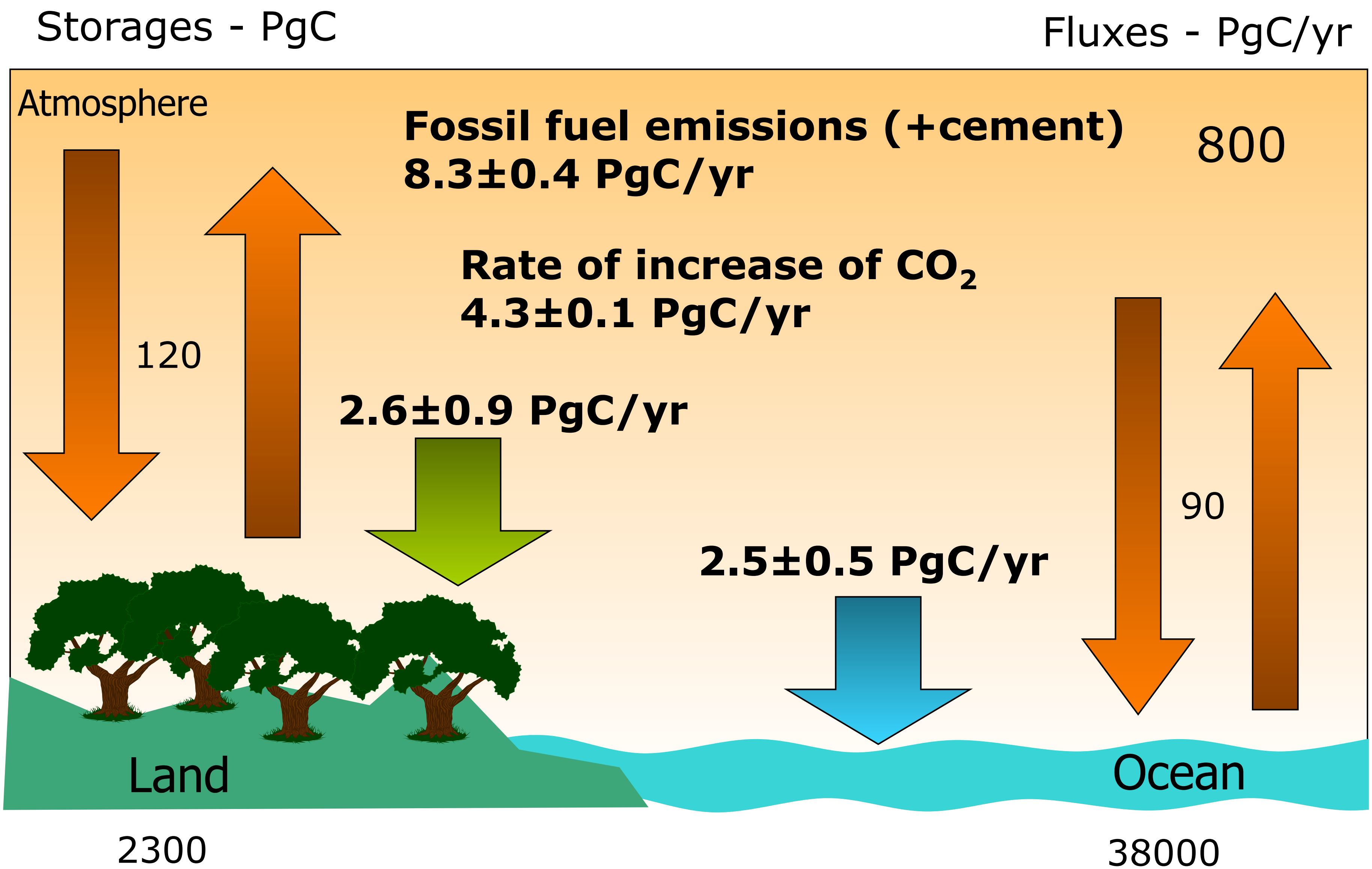
NASA Carbon Flux System



NASA Carbon Flux System

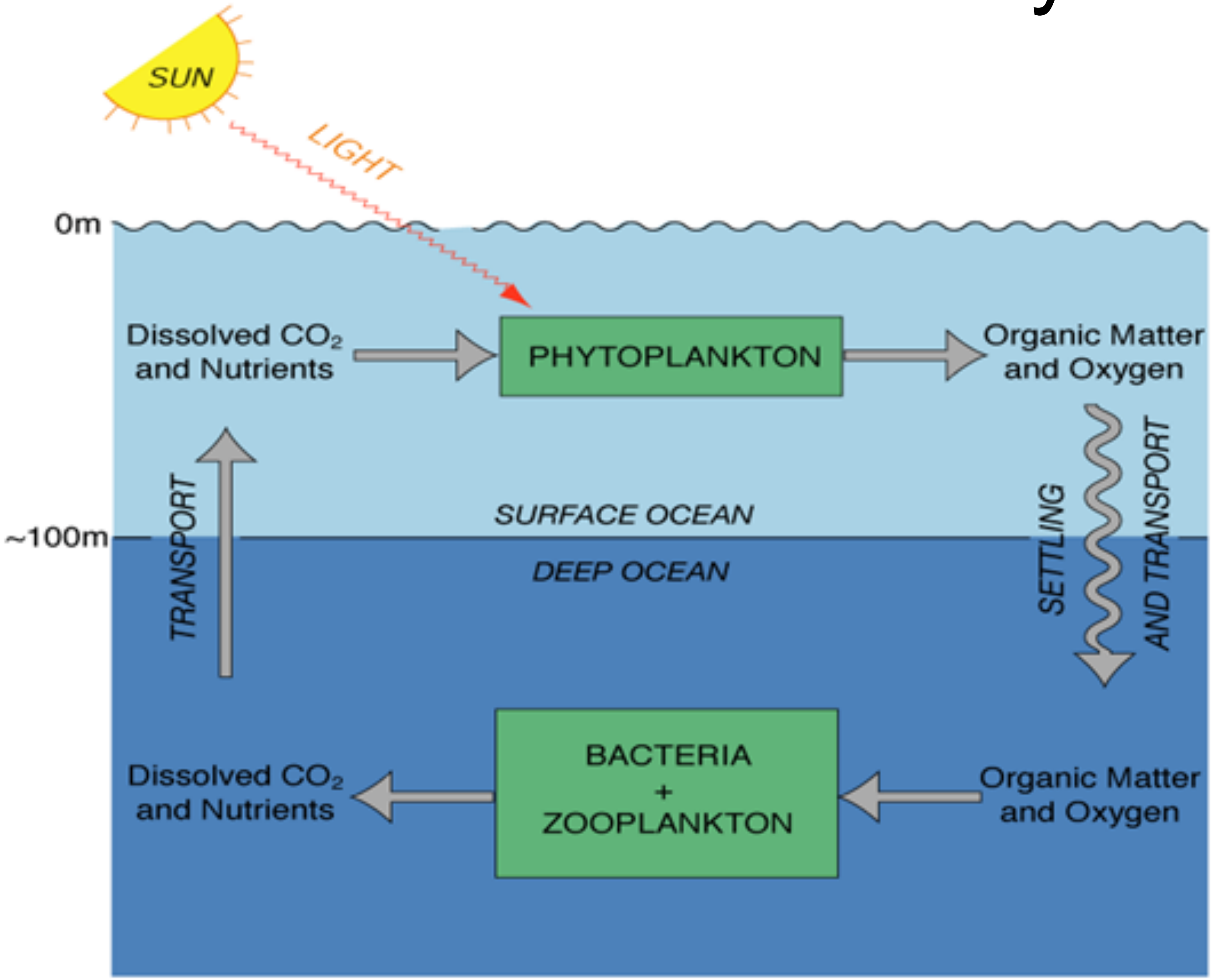


Global CO_2 Budget 2002-2011

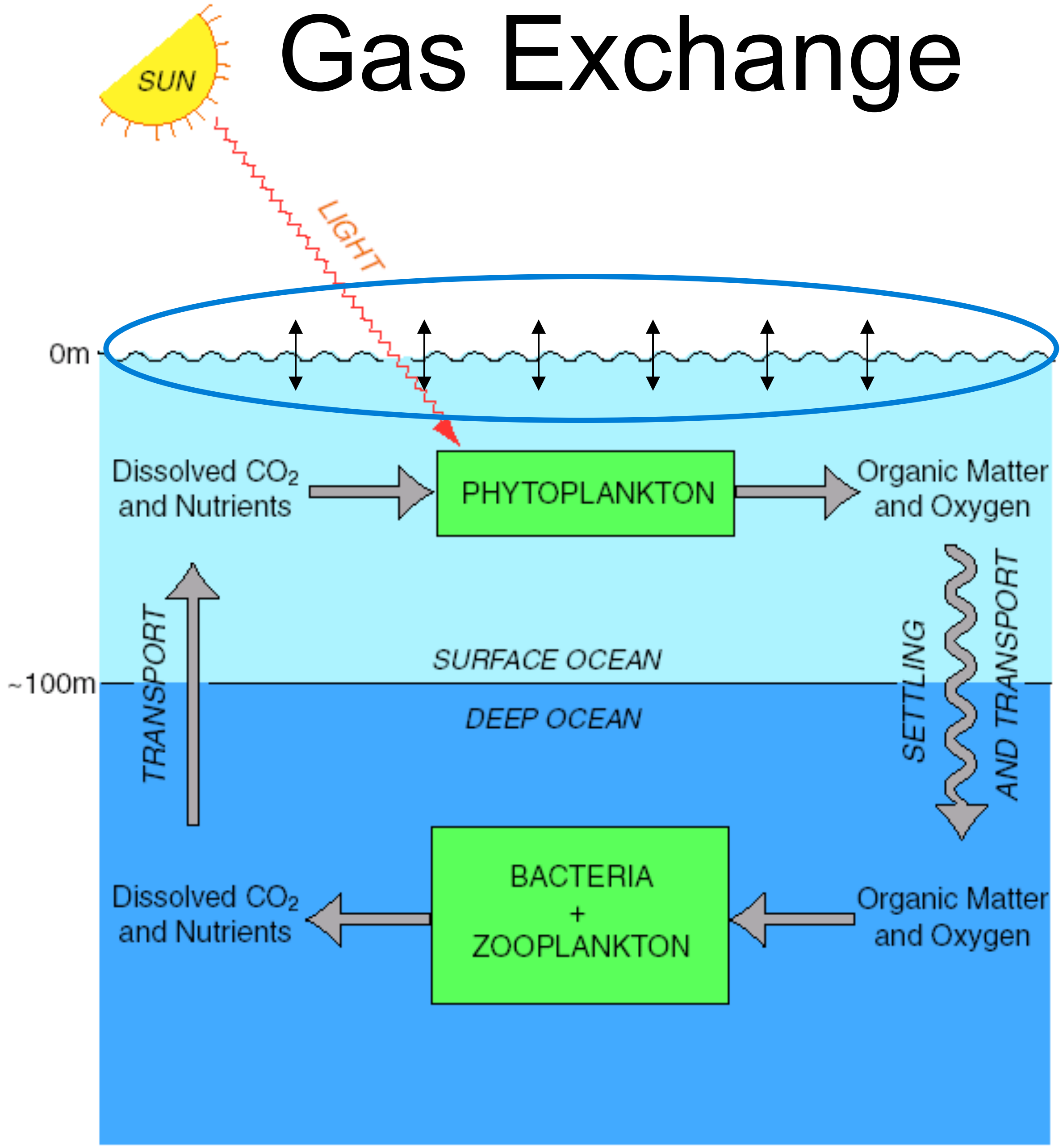


2002-2011 Fluxes: Le Quéré et al., 2012

The Oceanic Carbon Cycle



Gas Exchange



Gas Exchange:
The Response to Disequilibrium

$$\frac{dC}{dt} = K * (C - C_A)$$

Rate of change of gas concentration in water

Rate constant of gas exchange

Disequilibrium between gas concentration (C) and its saturation (C_A)

Dissolved gases reach new equilibrium with air by
1) **outgassing when supersaturated ($C > C_A$)**
2) **ingassing when undersaturated ($C < C_A$).**

$$K = \frac{k_w}{z_{ML}}$$

Piston Velocity [m/day]

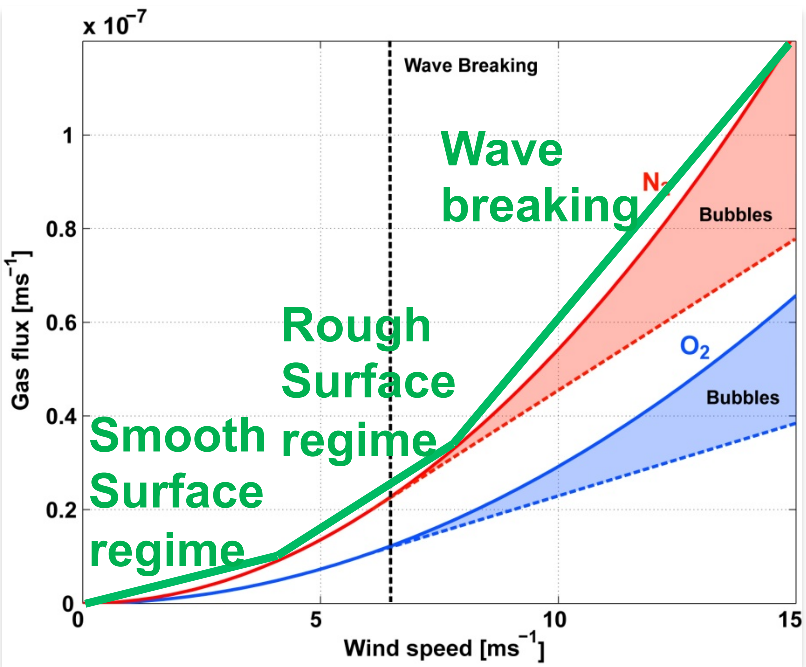
Mixed Layer Depth [m]

$$= 1/\tau_{res}$$

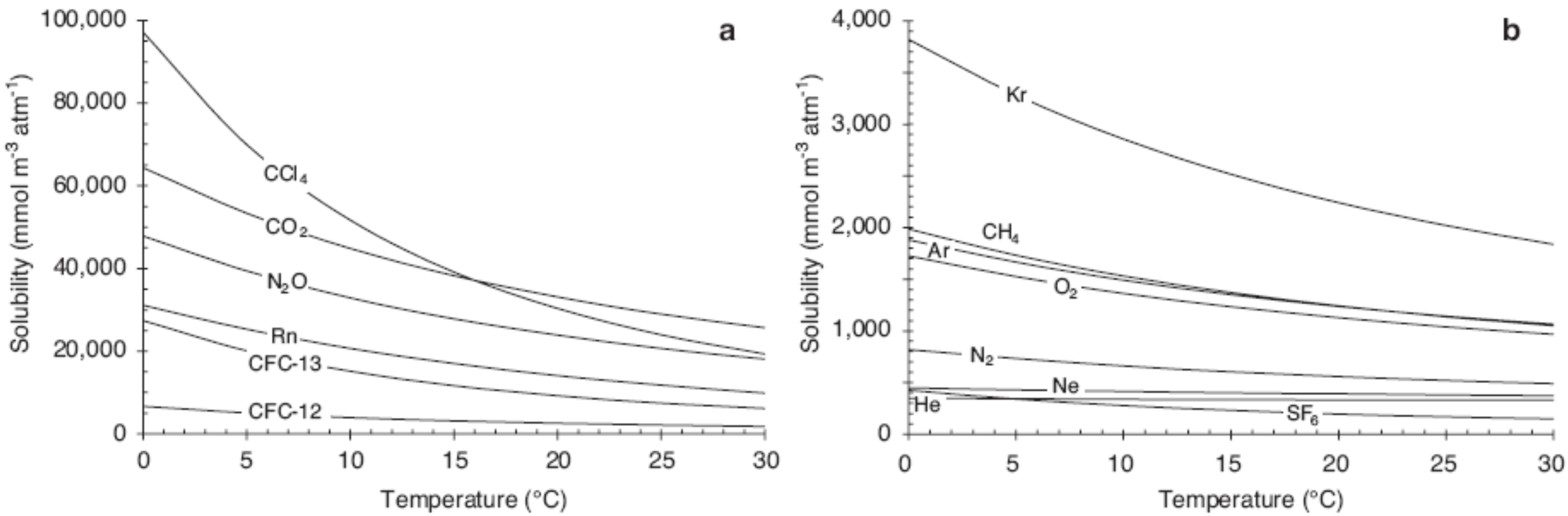
Residence time for Gas exchange [day]

Air-Sea Gas Exchange

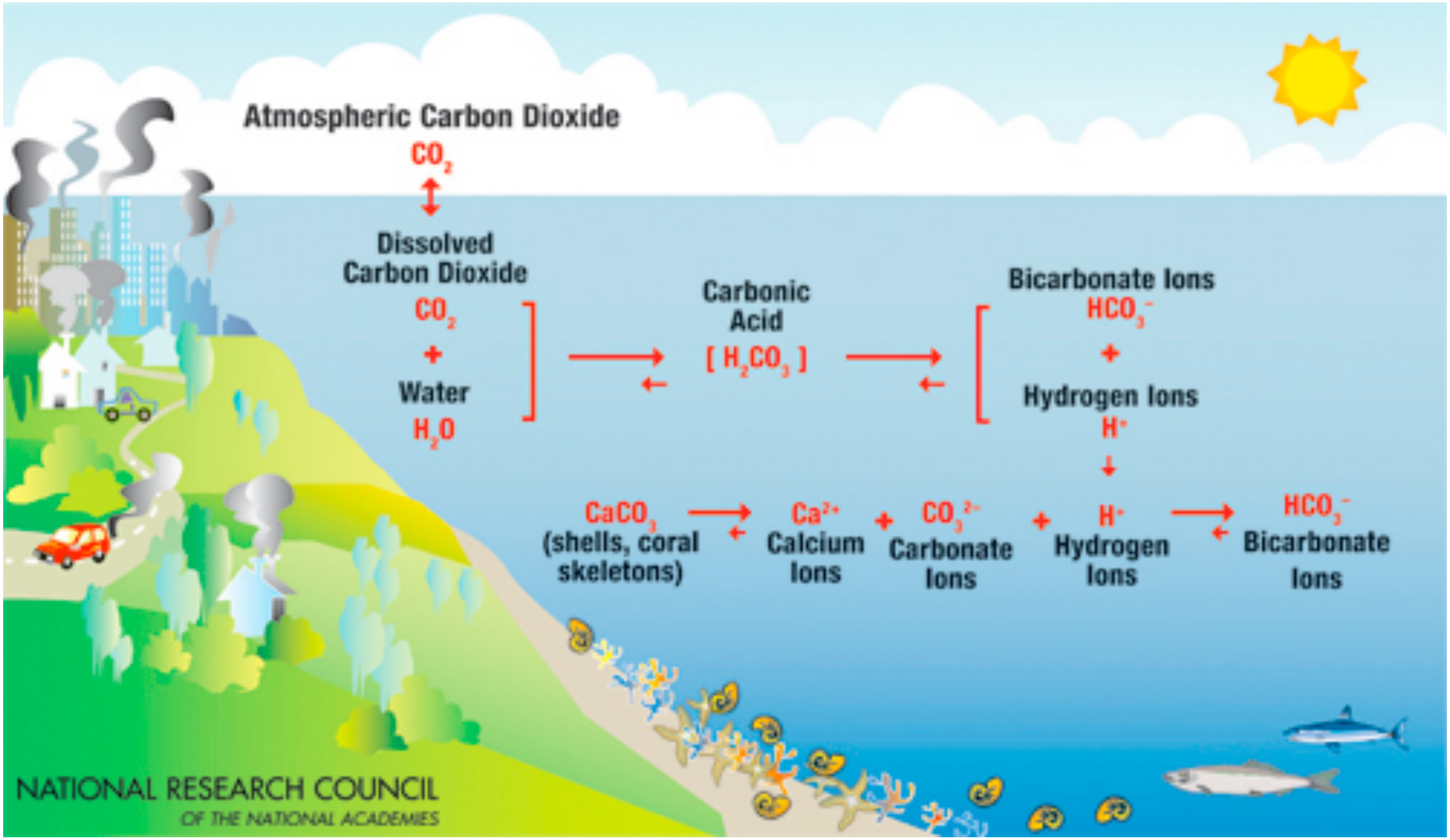
Gas exchange between atmosphere and ocean is mainly caused by diffusion and gas bubble injection. Both processes increase for all gases with wind speed. Some gases, such as CO_2 or O_2, are also affected by biogeochemical processes in the ocean.



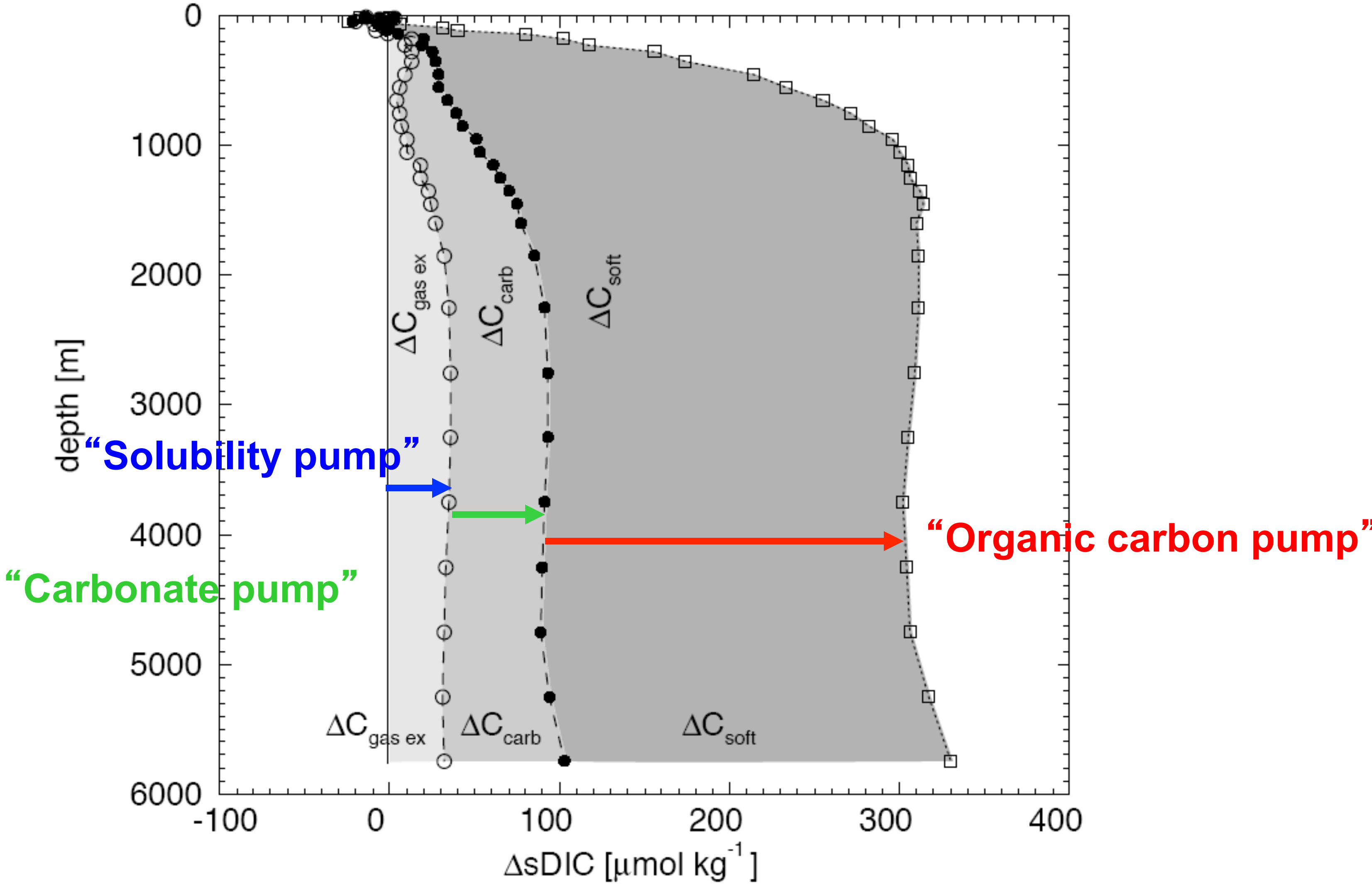
Gas Solubility



Carbon in the Ocean



The Three Carbon "Pumps"



Fate of Anthropogenic CO_2 Emissions (2002-2011 average)

8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

4.3±0.1 PgC/yr
46%

2.6±0.8 PgC/yr
28%
Calculated as the residual
of all other flux components

26%
2.5±0.5 PgC/yr

Source: Le Quéré et al. 2012; Global Carbon Project 2012

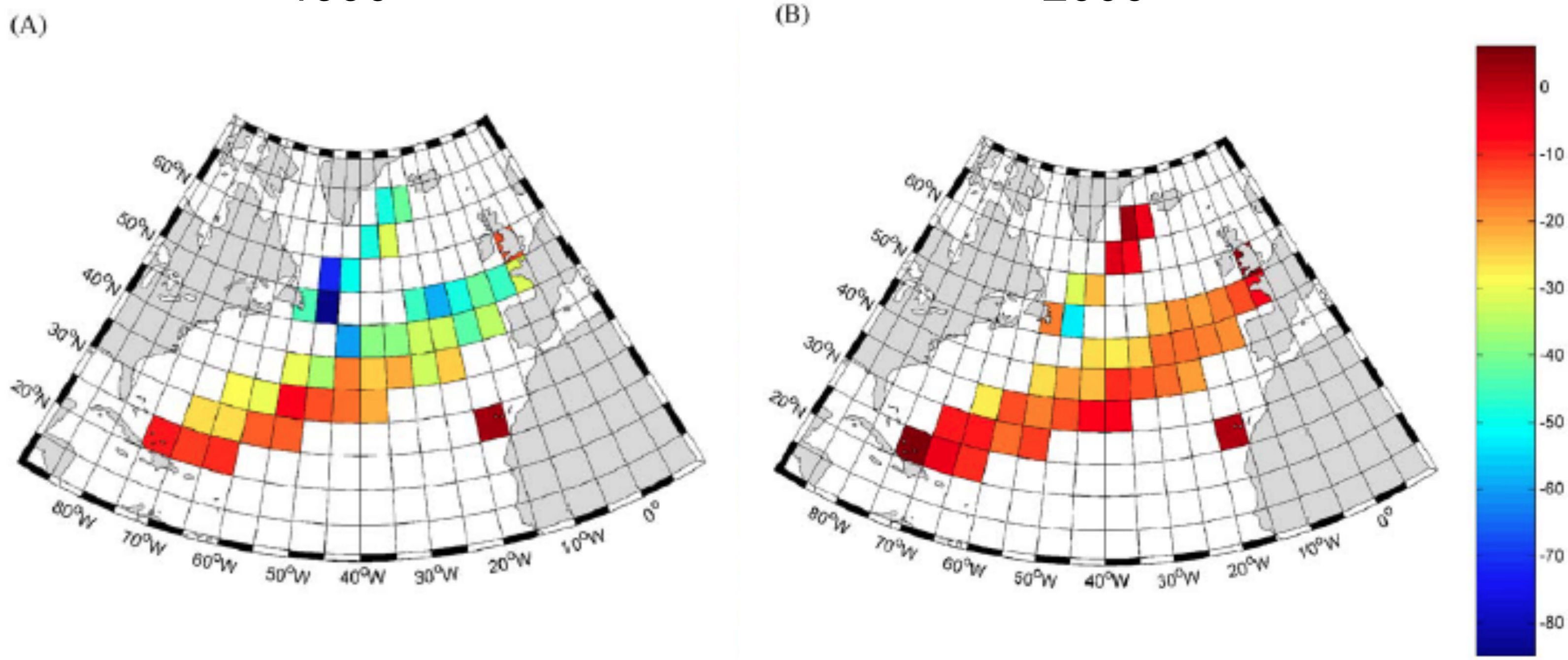
Oceanic Carbon Cycle: Changes and Feedbacks

- Solubility change with temperature
- Effect of warming on stratification
  - Warming tends to enhance stratification
  - Reduced mixing
  - Less nutrient availability and less phytoplankton production
  - Enhanced variability in primary production and carbon export flux to the deep sea
- Changes in biological pump
  - Biological Production depends on temperature
- Weakening of Southern Ocean sink
  - Attributed to the observed increase in Southern Ocean winds (resulting from human activities, and projected to continue in the future)
  - Reduction of the efficiency of the Southern Ocean sink of CO_2 in the short term (about 25 years)
  - Possibly a higher level of stabilization of atmospheric CO_2 on a multi-century time scale)
- Intermediate carbon storage in mode waters

Observed weakening of the North Atlantic CO_2 sink

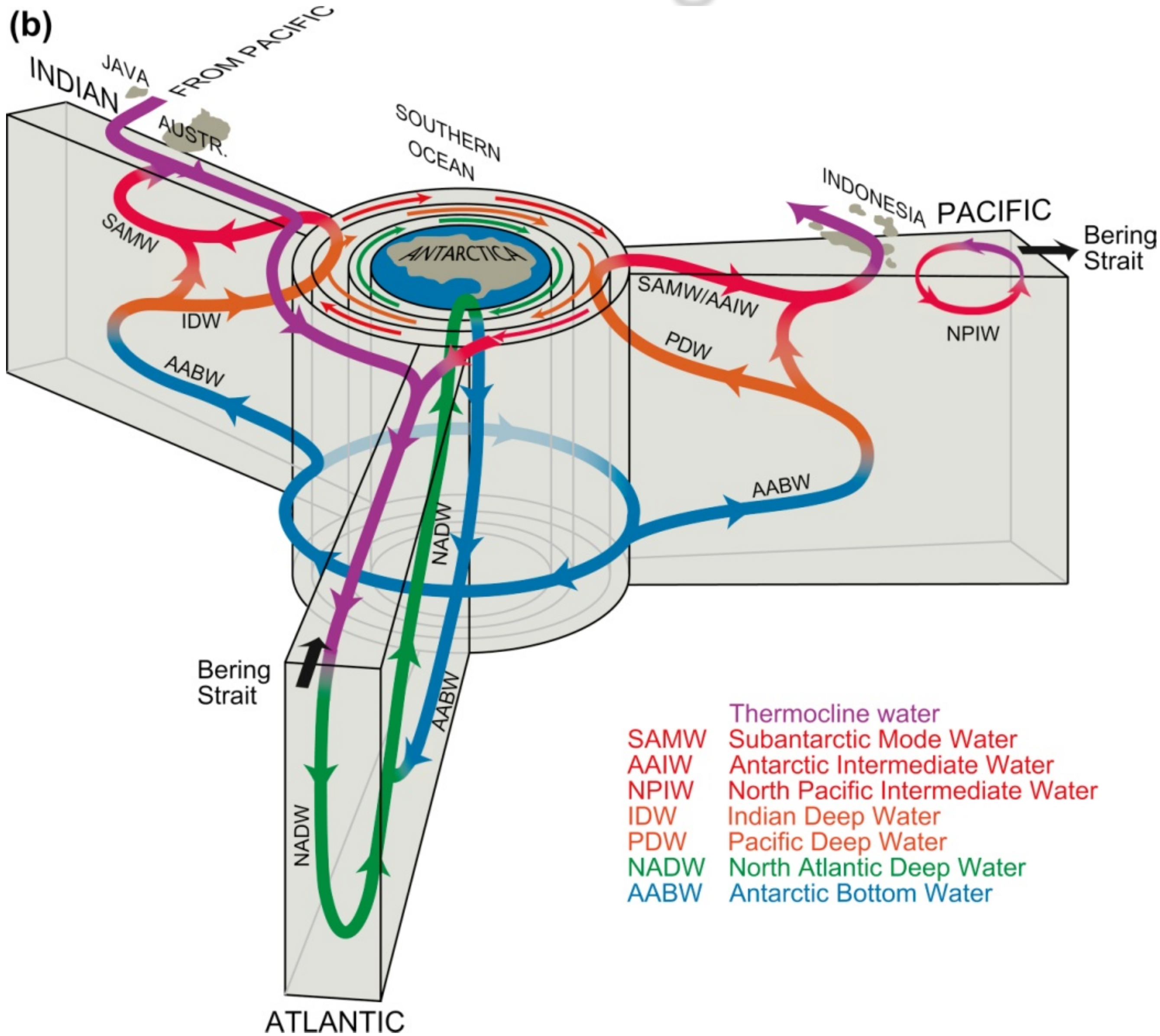
Difference in air-sea CO_2 concentration [μatm]
(sea-surface – atmosphere)

1990 2006



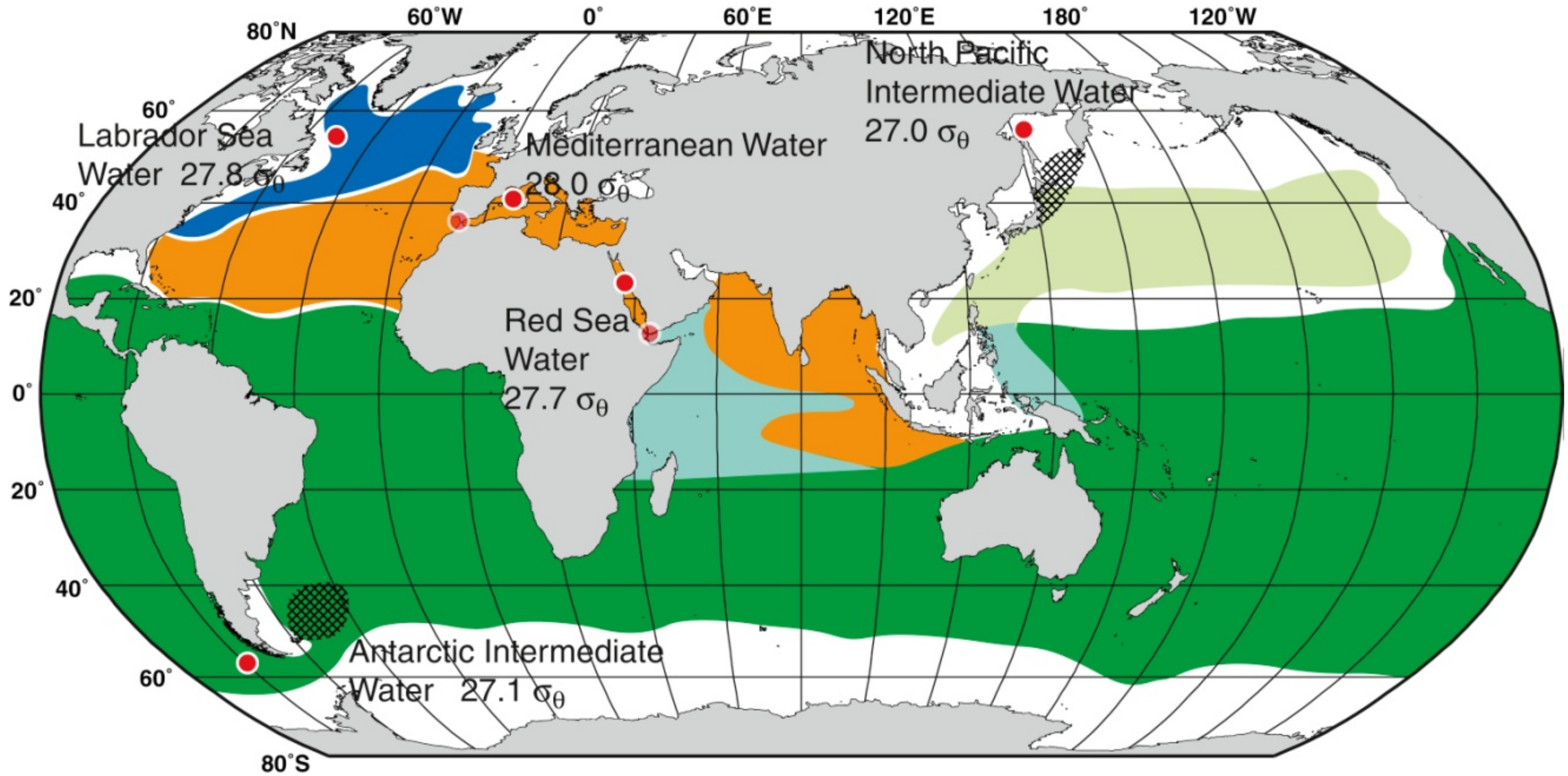
Schuster et al., 2007

Global Overturning Schematics



Slide: Talley et al. (2011), Copyright © Elsevier Inc.

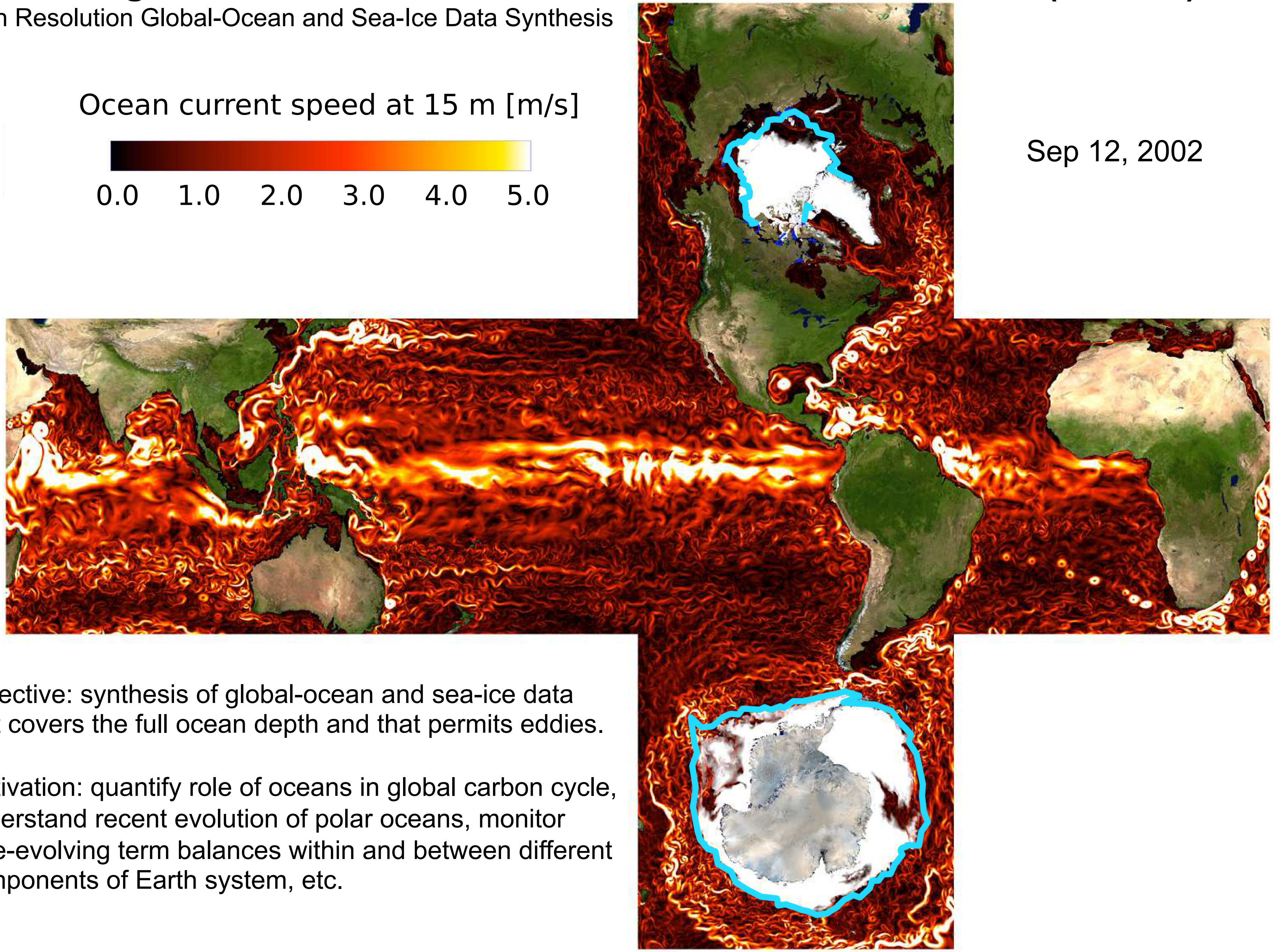
Intermediate Waters



After Talley (2008).

Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2)

High Resolution Global-Ocean and Sea-Ice Data Synthesis

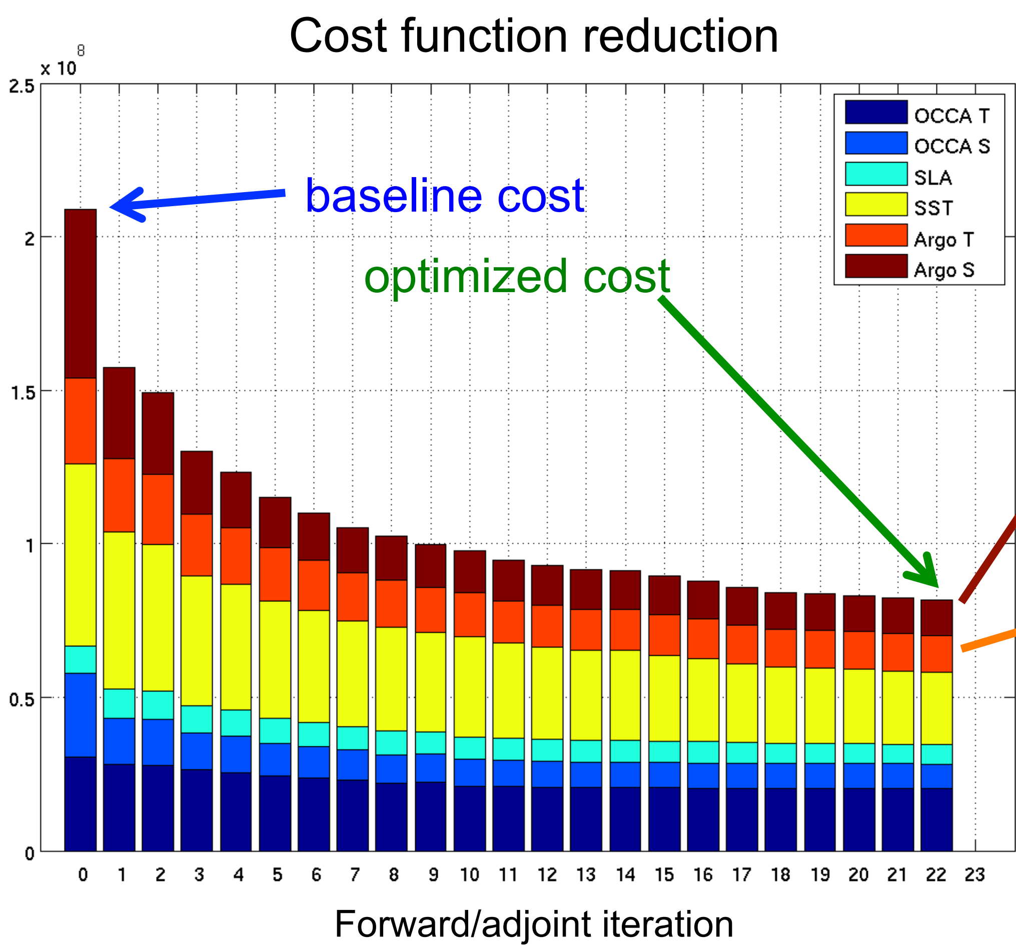


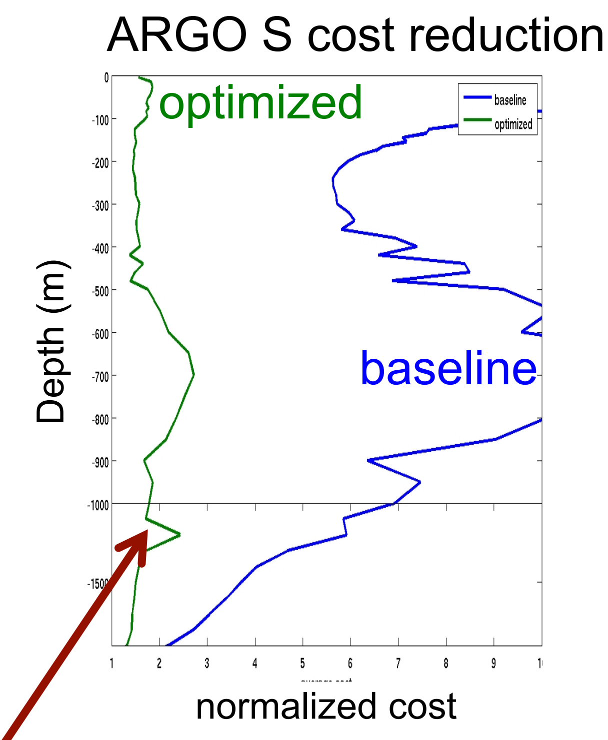
Objective: synthesis of global-ocean and sea-ice data that covers the full ocean depth and that permits eddies.

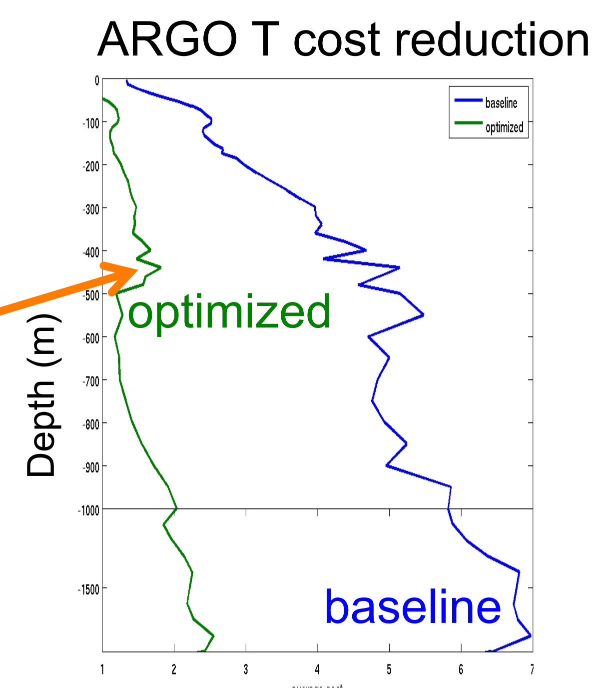
Motivation: quantify role of oceans in global carbon cycle, understand recent evolution of polar oceans, monitor time-evolving term balances within and between different components of Earth system, etc.

Adjoint-method optimization of the physical global-ocean and sea ice model

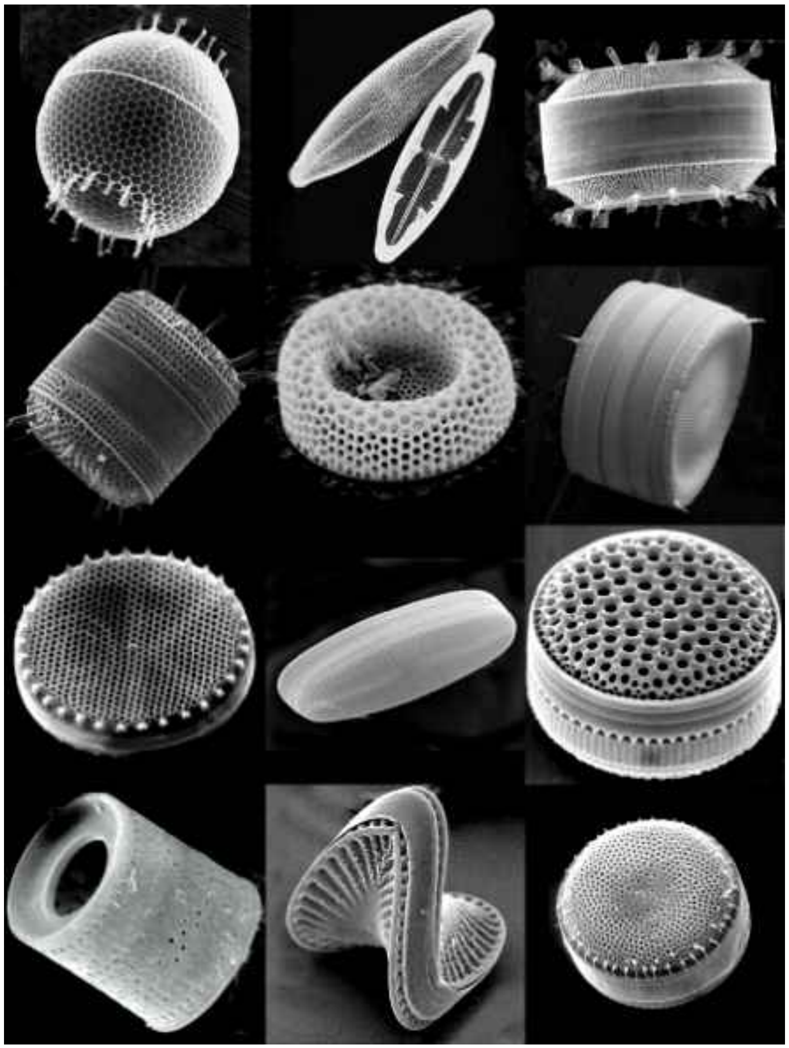
- Data constraints currently include JASON SLA, AMSR-E SST, ARGO T/S profiles, and OCCA T/S climatology.
- Control variables are initial T/S and atmospheric boundary conditions (wind, precipitation, air temperature and humidity, incoming radiation).







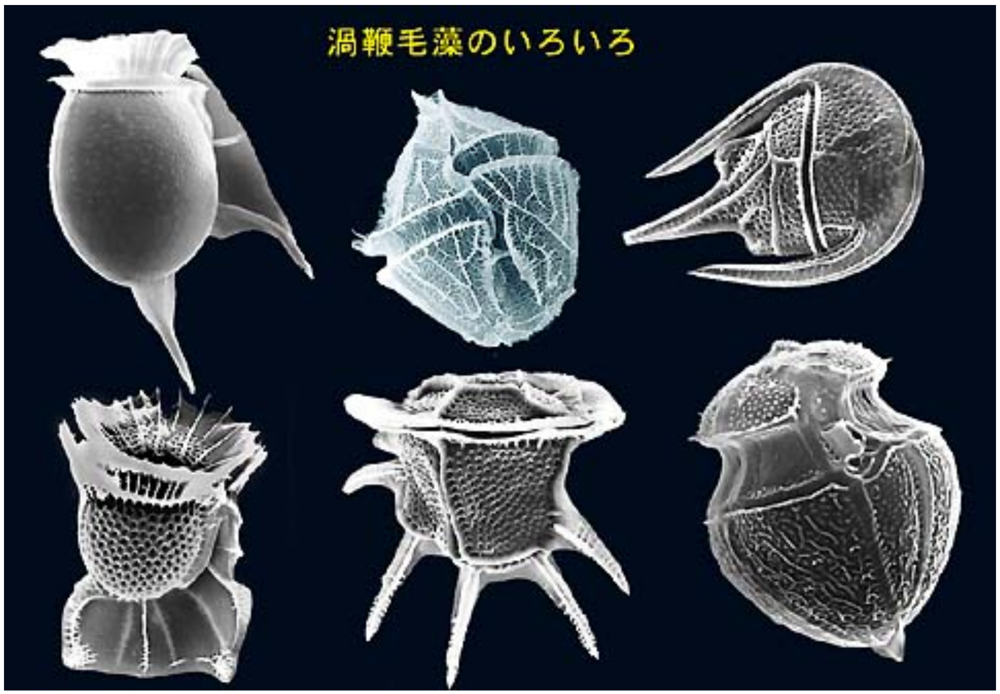
Diatoms



Unicellular, cell walls made of silica, most abundant phytoplankton in the ocean

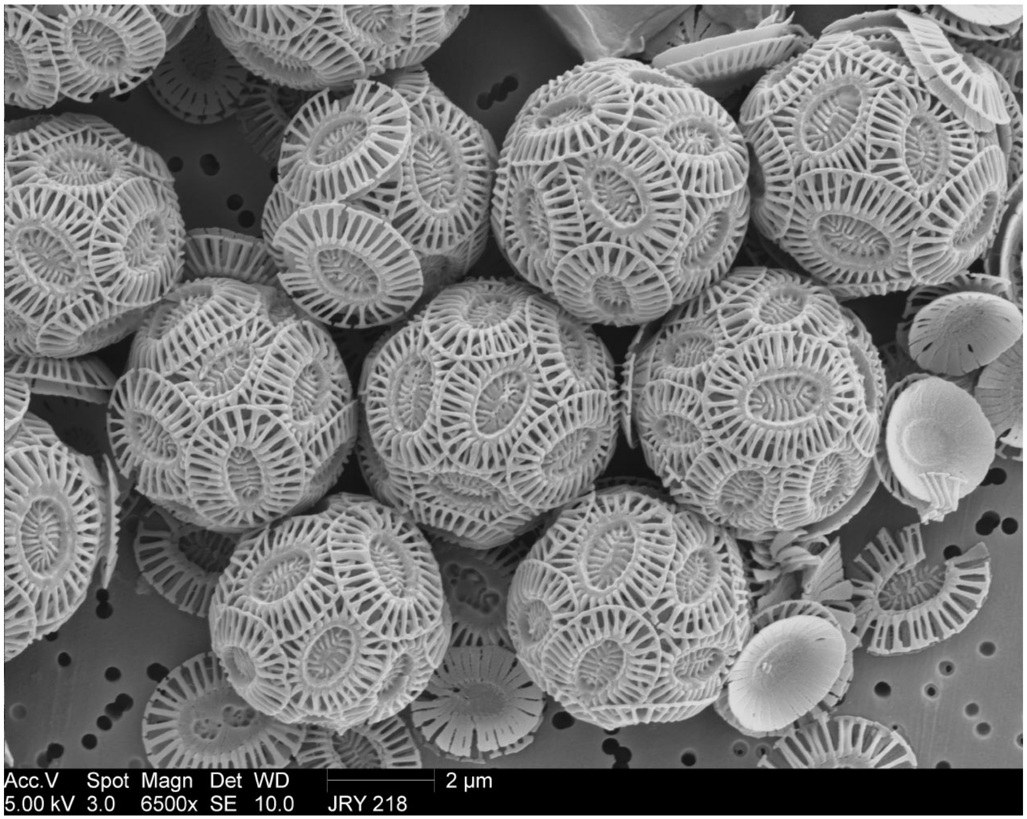
Dinoflagellates

Specialized conditions, mostly coastal



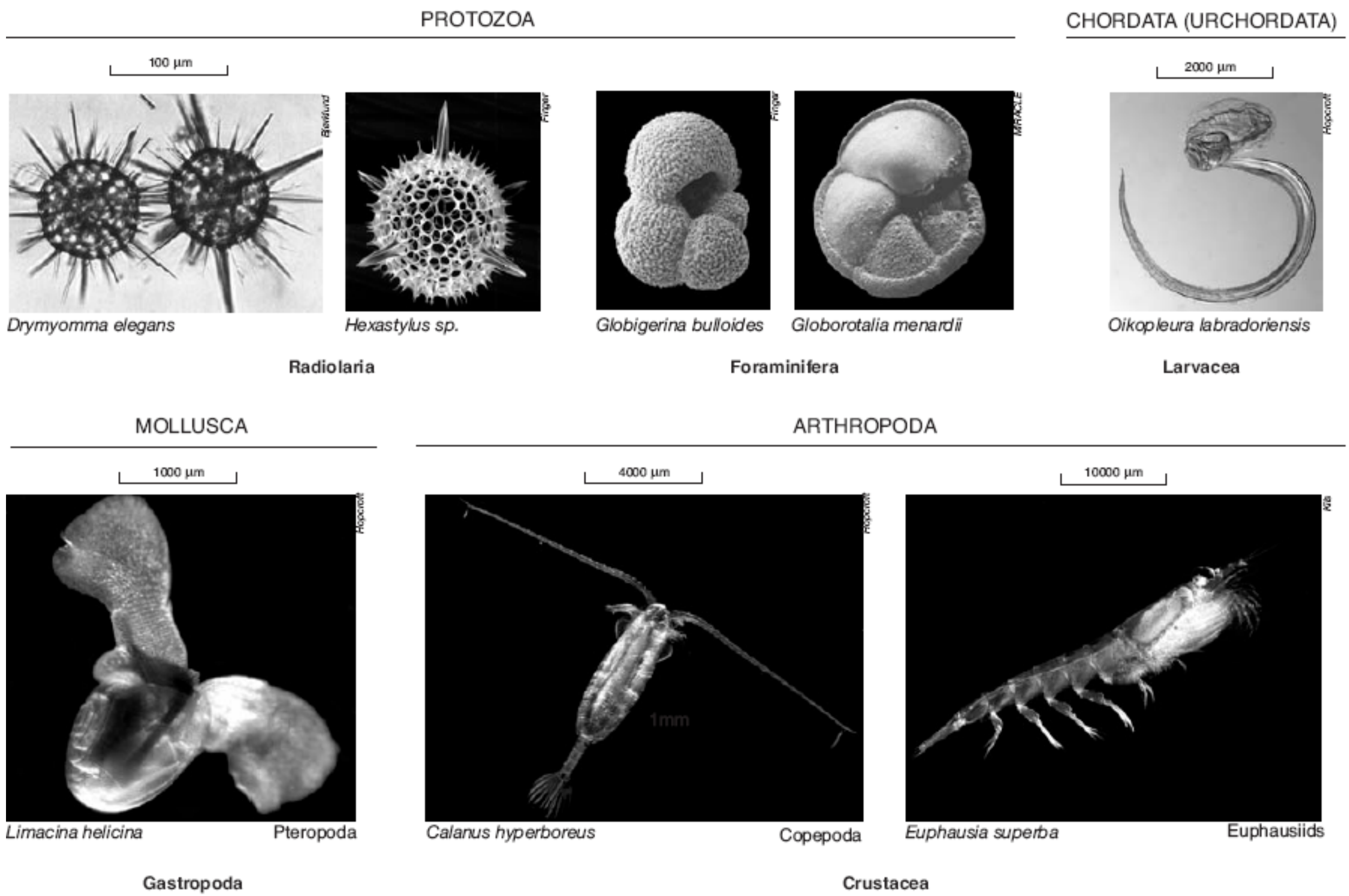
Coccolithophores

Can tolerate low light levels

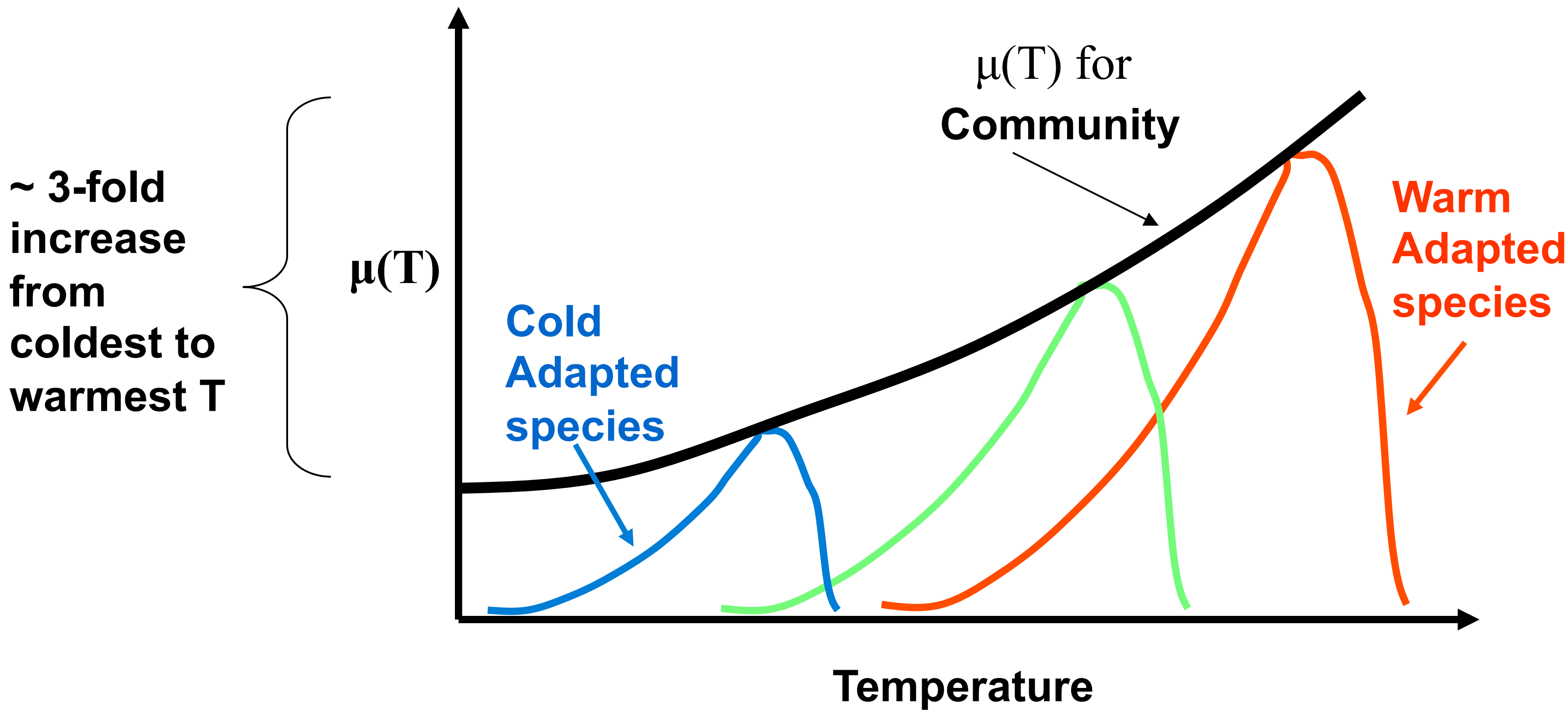


E. Huxleyi

Zooplankton



From Critters to Properties…

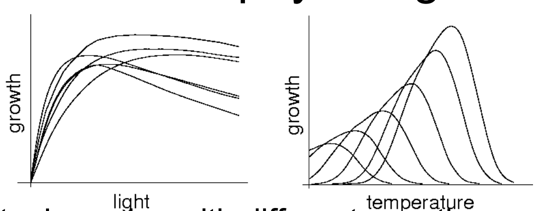


Darwin ecosystem model in ECCO2

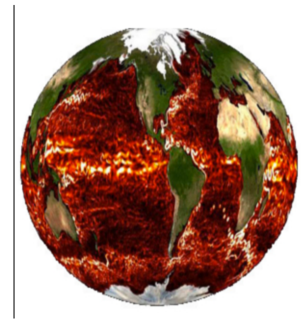
JPL
Holger Brix
Dimitris Menemenlis
Hong Zhang
MIT
Stephanie Dutkiewicz,
Mick Follows,
Oliver Jahn,
David Wang,
Chris Hill

Biogeochemical approach based on “self-organizing” principle
Follows et. al, Science, 2007.

physiological ↔ environmental

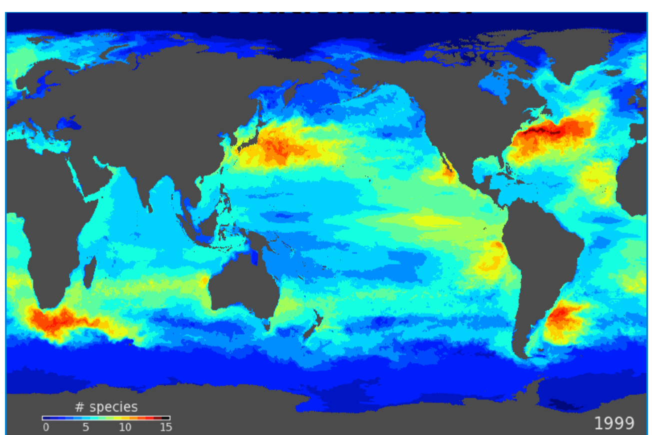


78 virtual species with different growth curves f(I,T,pH,…)

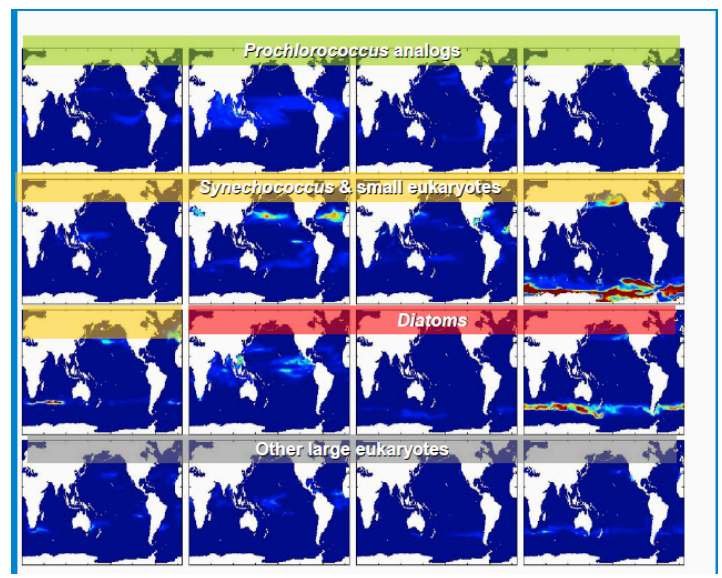


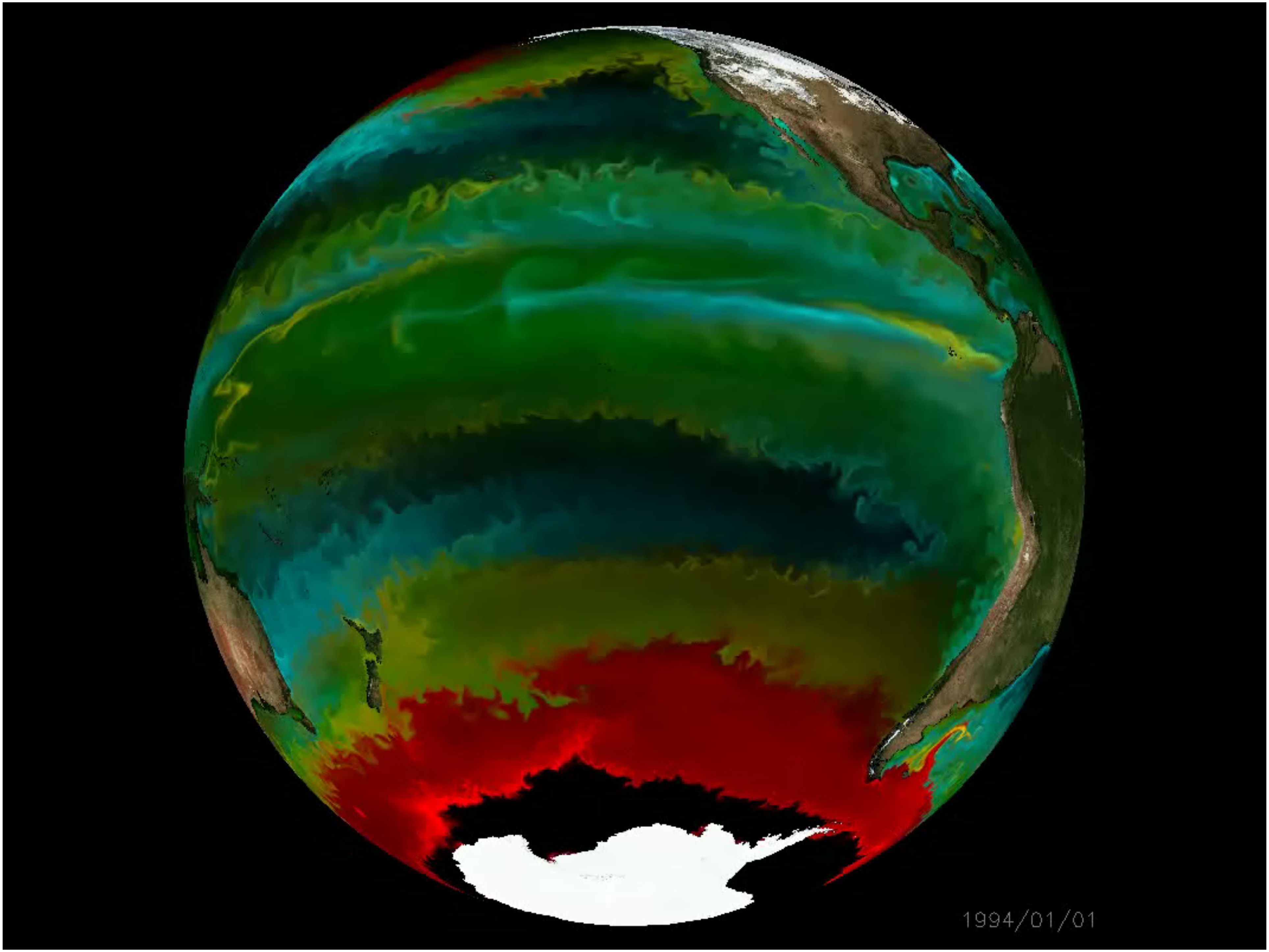
Ecosystem

Species abundance from 78 possible types in environment set by interplay between circulation, nutrients and physiology.



Number of co-existing phytoplankton types

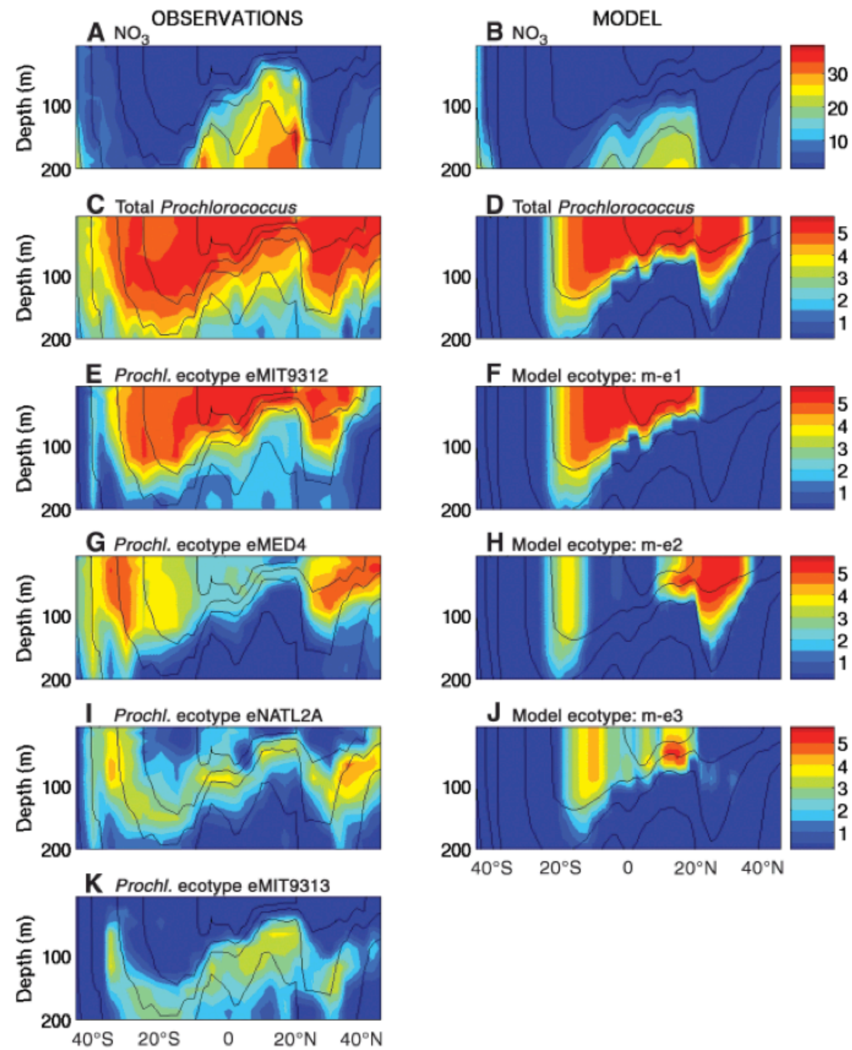



1994/01/01

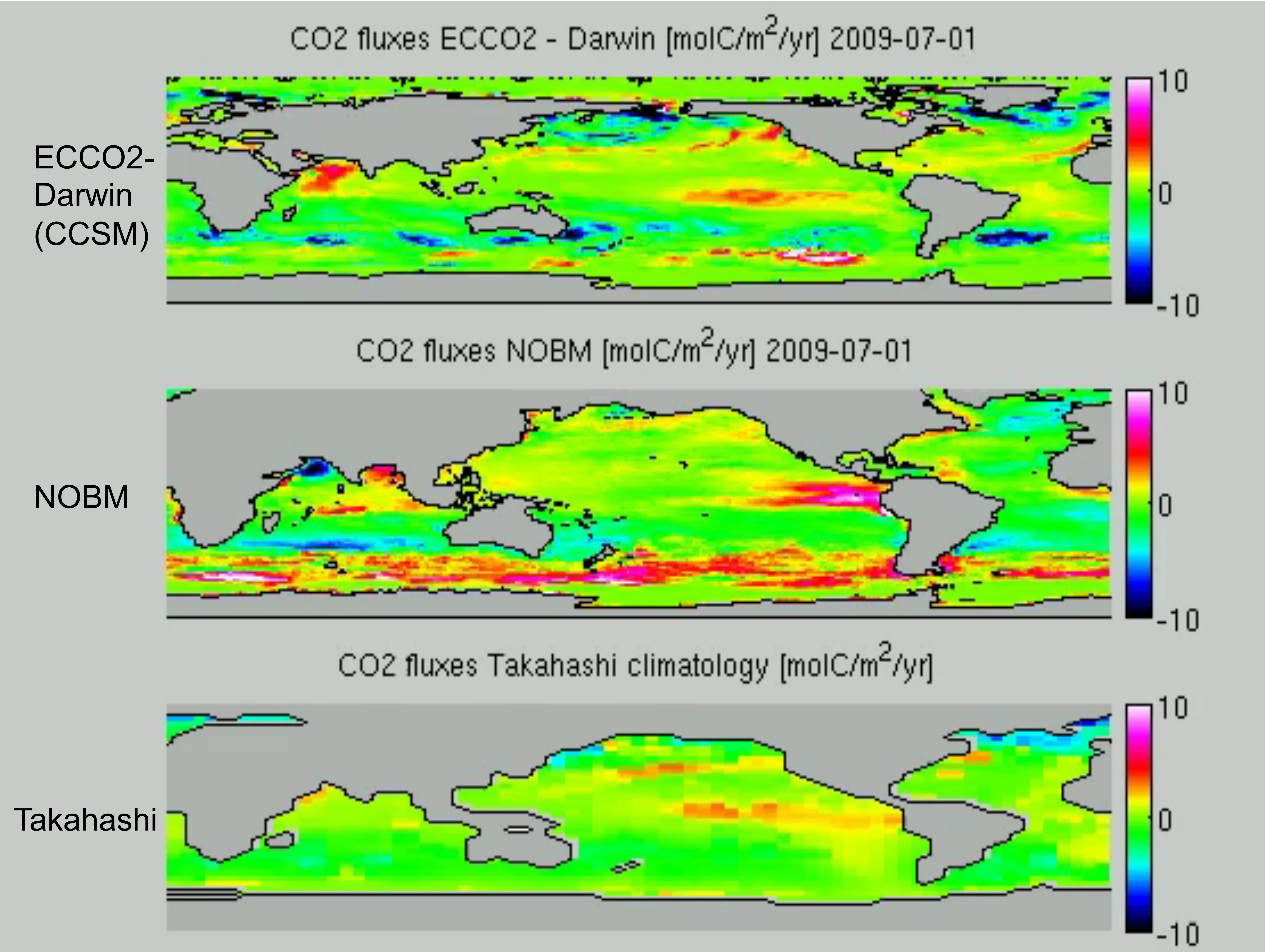
Connecting to CO_2 estimates

- ECCO2 + ecosystem ➔ alternate perspective on biological activity, species diversity
- For CMS nutrient source/sink terms include
  - carbon chemistry
  - carbon exchange with organic pool for each species is function of growth/decay

  ➔ provide a time evolving physical and biological environment for air-sea CO_2 flux estimates.
- Model initialization with results from coarser resolution model runs for nutrients and ecological fields (<u>only the 5 most successful species!</u>), climatological data sets for DIC, alkalinity, and O_2



Follows et. al, Science, 2007.


CO2 fluxes ECCO2 - Darwin [molC/m2/yr] 2009-07-01
ECCO2-Darwin (CCSM)
10
0
-10
CO2 fluxes NOBM [molC/m2/yr] 2009-07-01
NOBM
10
0
-10
CO2 fluxes Takahashi climatology [molC/m2/yr]
Takahashi
10
0
-10

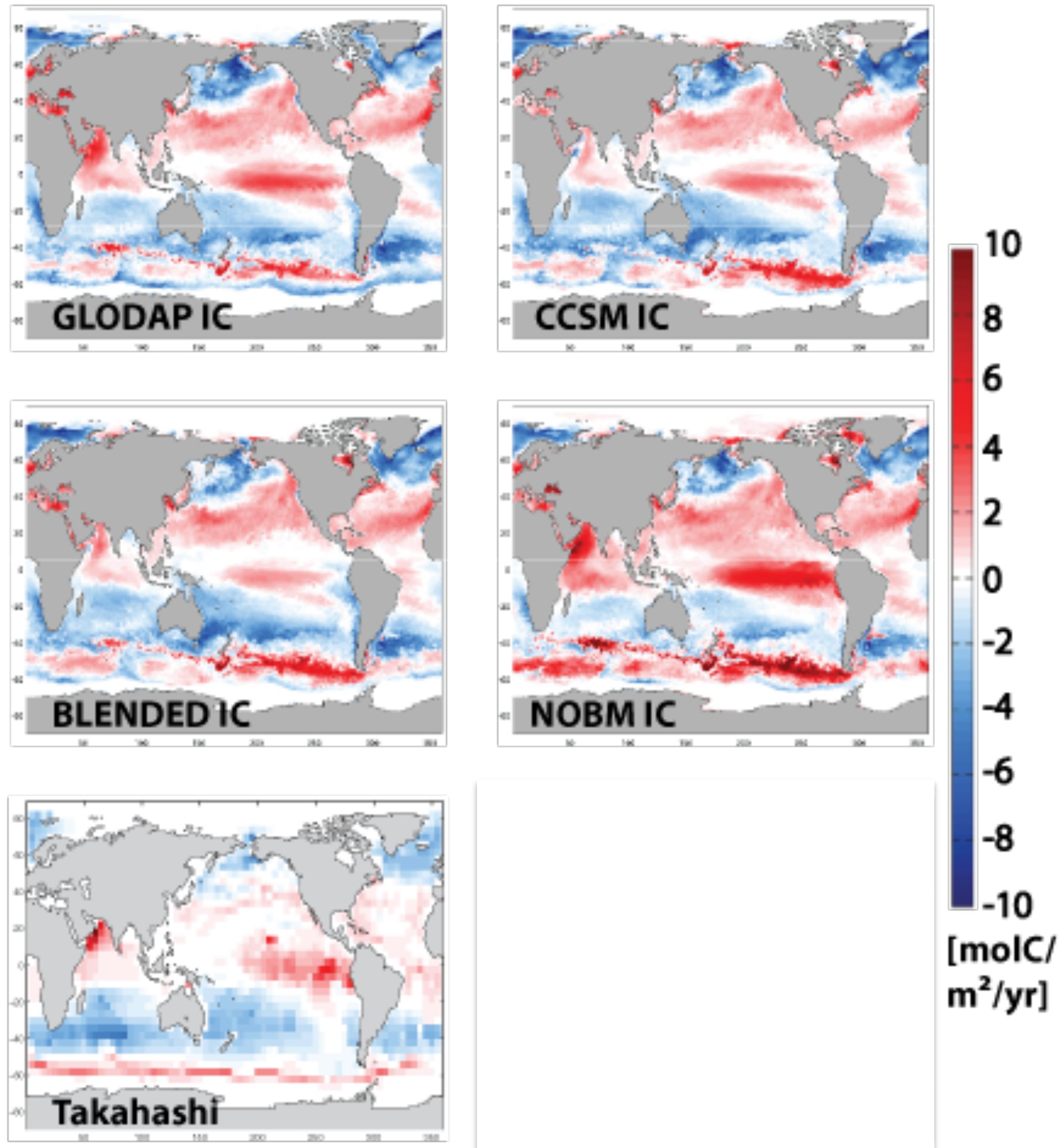
ECCO2-Darwin sensitivity experiments

The 13 ECCO2-Darwin integrations differ in:

- Their initial conditions (IC) for dissolved inorganic carbon (DIC), alkalinity (Alk), and oxygen:
  - **GLODAP:** DIC/Alk from GLODAP data set, O_2 from WOA 2005
  - **CCSM**: From earlier integration with CCSM biogeochemical model
  - **KS**: DIC blended from Key et al. and Sabine et al. data sets, Alk from GLODAP, O_2 from WOA 2005
  - **BLEND1**: Blend of modified **CCSM** and **KS** initial conditions
  - **BLEND2**: like BLEND1, with changed AABW values
  - **NOBM**: DIC and DOC from NOBM, Alk and O_2 from **BLEND**
  - **ETH:** DIC, Alk, O_2 all from WOA05
- Their parameterizations of
  - Air-sea gas exchange
  - Alkalinity dependence of calcium carbonate production
  - Dissociation constant
  - Diffusion

Simulated Carbon Fluxes

- Monthly means for July 2009
- Positive: upward flux



Adjustment of Ocean Biogeochemistry Model (OBM)

Least squares method based on computation of model Green's functions.

Previously used for, e.g., ocean circulation estimates (Stammer and Wunsch, 1996; Menemenlis et al., 1997; 2005), atmospheric tracer inversions (Enting and Mansbridge, 1989; Tans et al., 1990; Bousquet et al., 2000), ocean carbon inversions (Gloor et al., 2003; Mikaloff Fletcher et al., 2006; 2007), and joint ocean-atmosphere carbon dioxide inversions (Jacobson et al., 2007a; 2007b).

OBM:

$$\mathbf{s}\,(t+1) \;=\; M\,[\mathbf{s}\,(t),\,\mathbf{x}]$$

s(t) is the OBM state vector at time t
M represents the numerical model
x is a set of control parameters

Data:

$$\mathbf{y} \;=\; H\,[\mathbf{s}] + \mathbf{n} \;=\; G\,[\mathbf{x}] + \mathbf{n}$$

y is the available observations
H is the measurement model
G is a function of *M* and *H*
n is additive noise

Cost function:

$$J \;=\; \mathbf{n}^{T}\,\mathbf{R}^{-1}\,\mathbf{n}$$

J is a cost function, where it is assumed that $<\mathbf{x}>$, $<\mathbf{n}>$, and $<\mathbf{x}\mathbf{x}^{T}> \sim \mathbf{0}$; and $<\mathbf{n}\mathbf{n}^{T}> = \mathbf{R}$

Linearization:

$$\boldsymbol{y} - G\,[\mathbf{x}_b] \;\approx\; \mathbf{G}\,(\mathbf{x} - \mathbf{x}_b) + \mathbf{n}$$

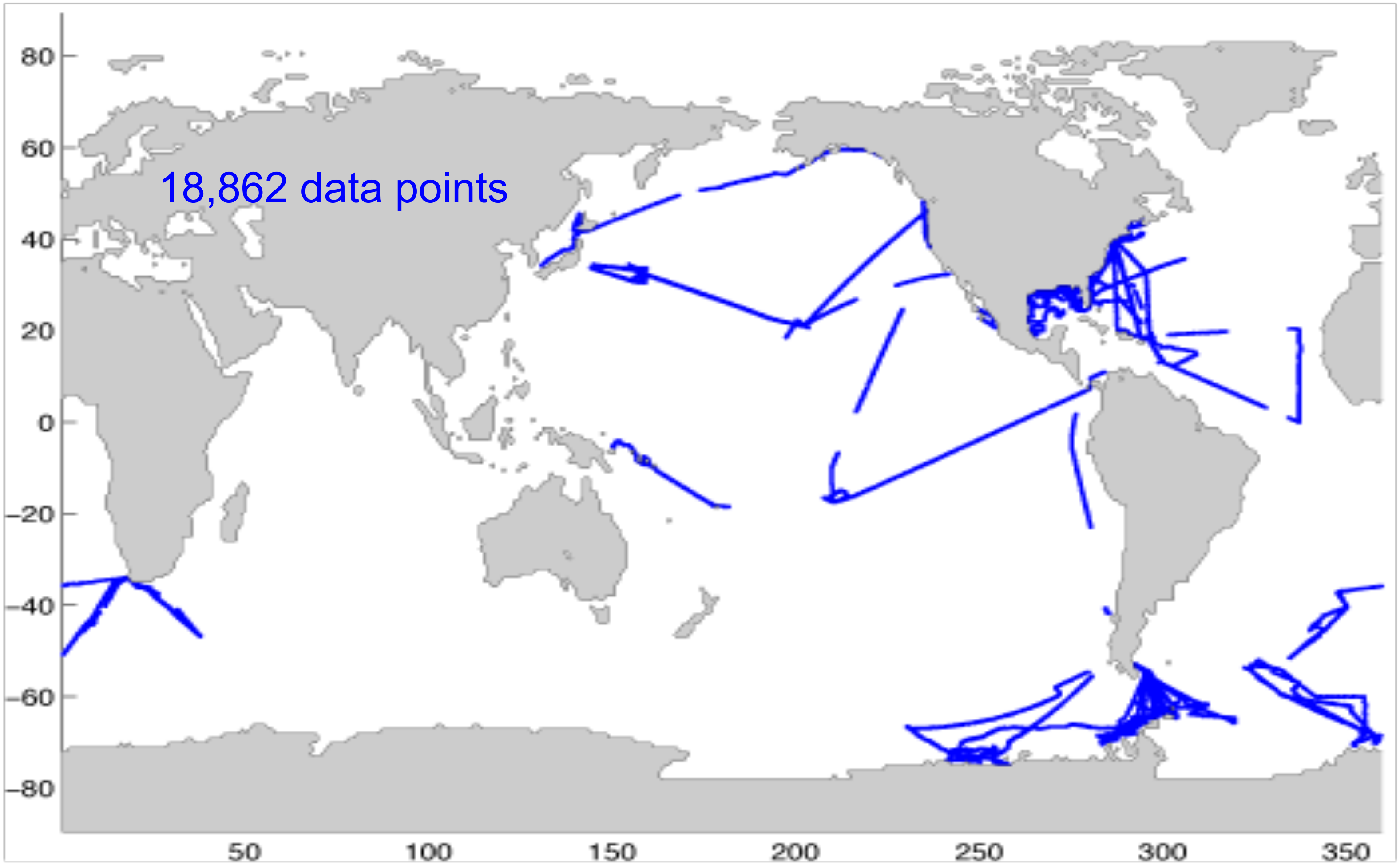
G is a kernel matrix whose columns are computed using OBM sensitivity experiment for each parameter in vector **x**.
Subscript "b" represents baseline OBM integration used to linearize problem.

Solution:

$$\tilde{\mathbf{x}} \;=\; \mathbf{x}_b + (\mathbf{G}^{T}\,\mathbf{R}^{-1}\,\mathbf{G})^{-1}\,\mathbf{R}^{-1}\,\mathbf{G}^{T}\,(\boldsymbol{y} - G\,[\mathbf{x}_b])$$

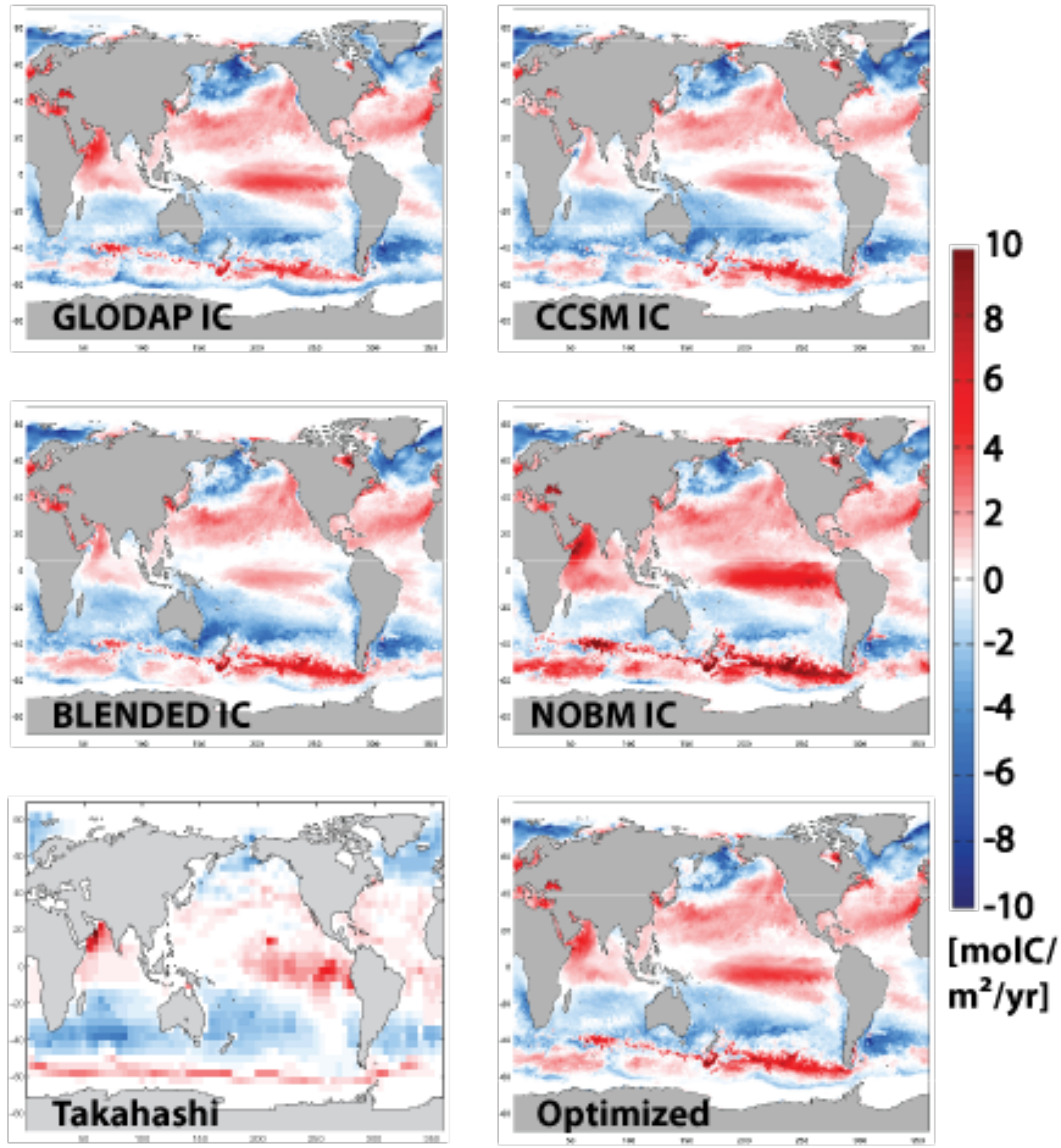
Control parameters that minimize cost function *J*

A first proof-of-concept assimilation of LDEO pCO_2 data for 2009-2010

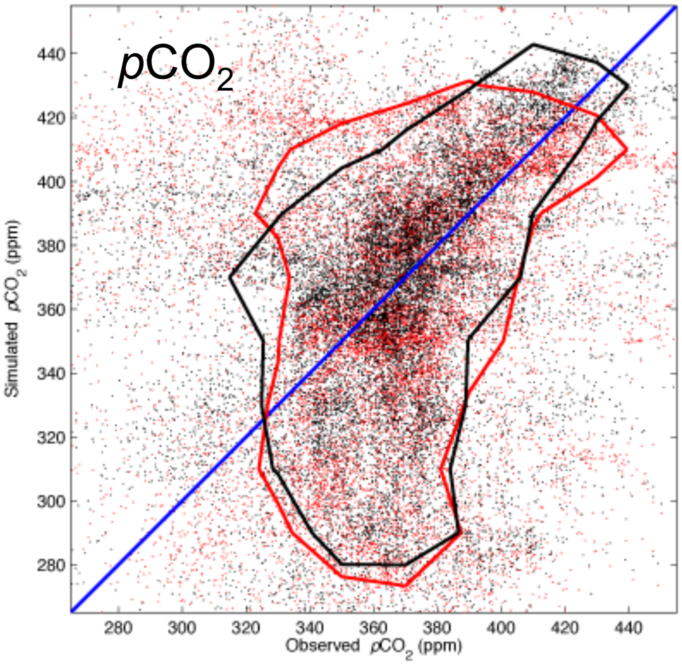


Simulated Carbon Fluxes

- Monthly means for July 2009
- Positive: upward flux ↑

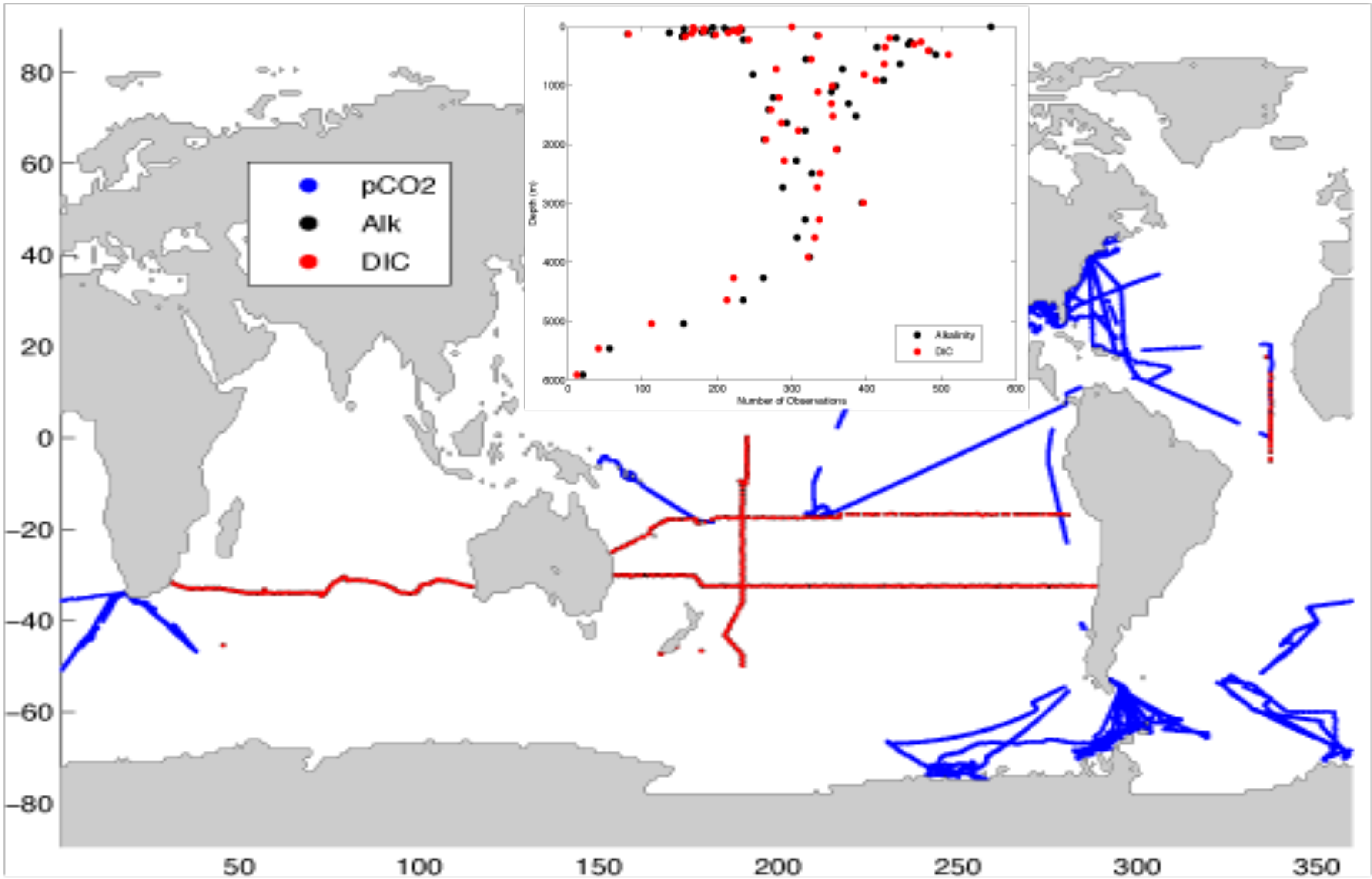


Model vs. Data



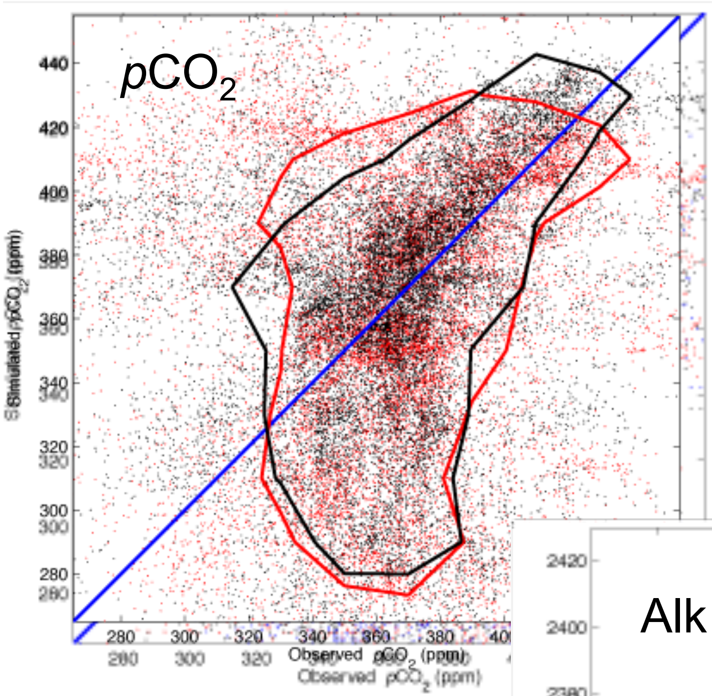
Version 1
Optimized

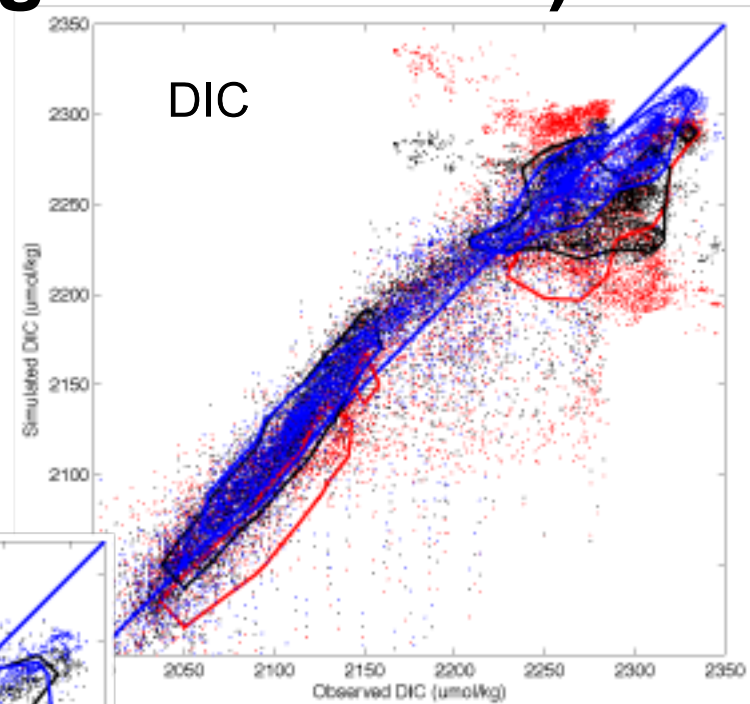
Adding DIC and alkalinity data for 2009-2010

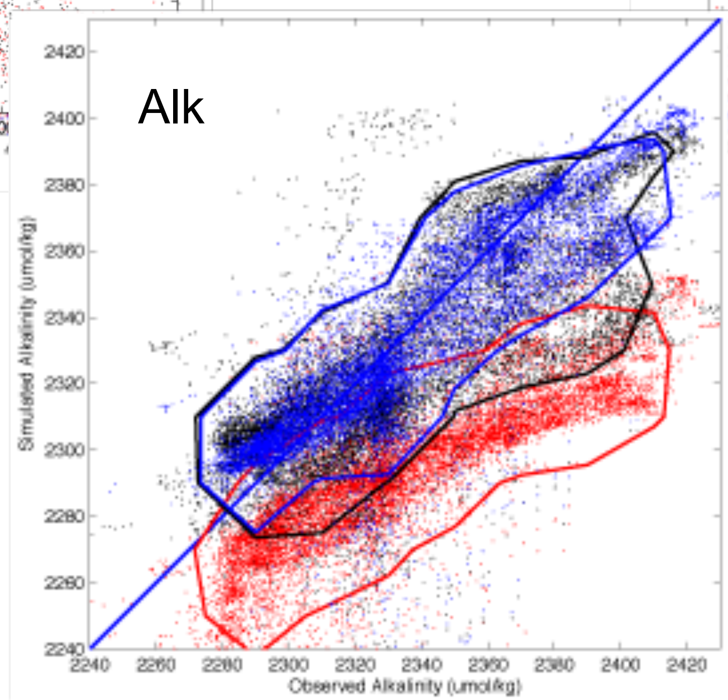


18,862 pCO2 data points, 13,168 Alk, 13,501 DIC

Model vs. Data (adding DIC and Alk)



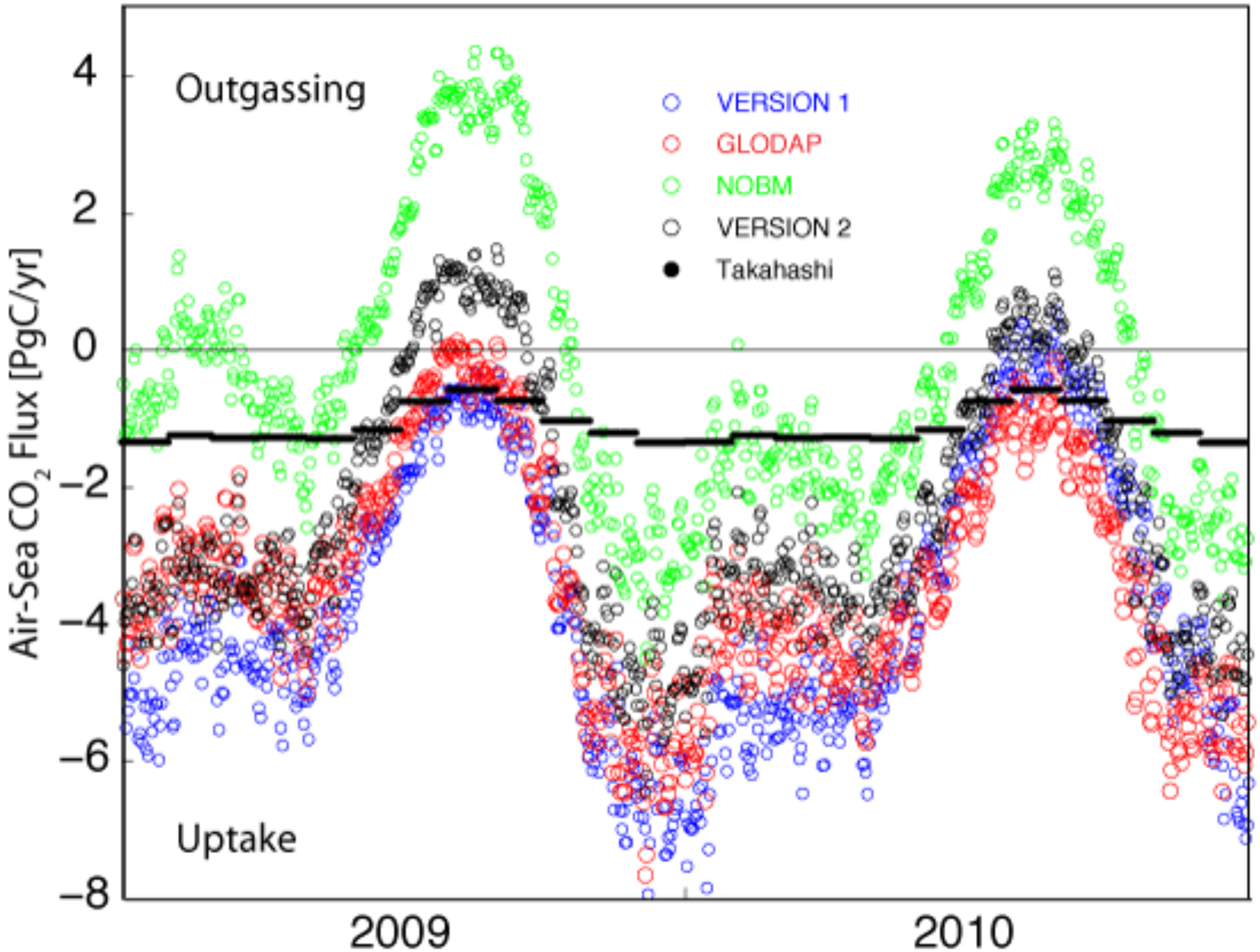




Version 1
Optimized
with pCO_2
only

Optimized with
pCO_2, DIC, and
Alk

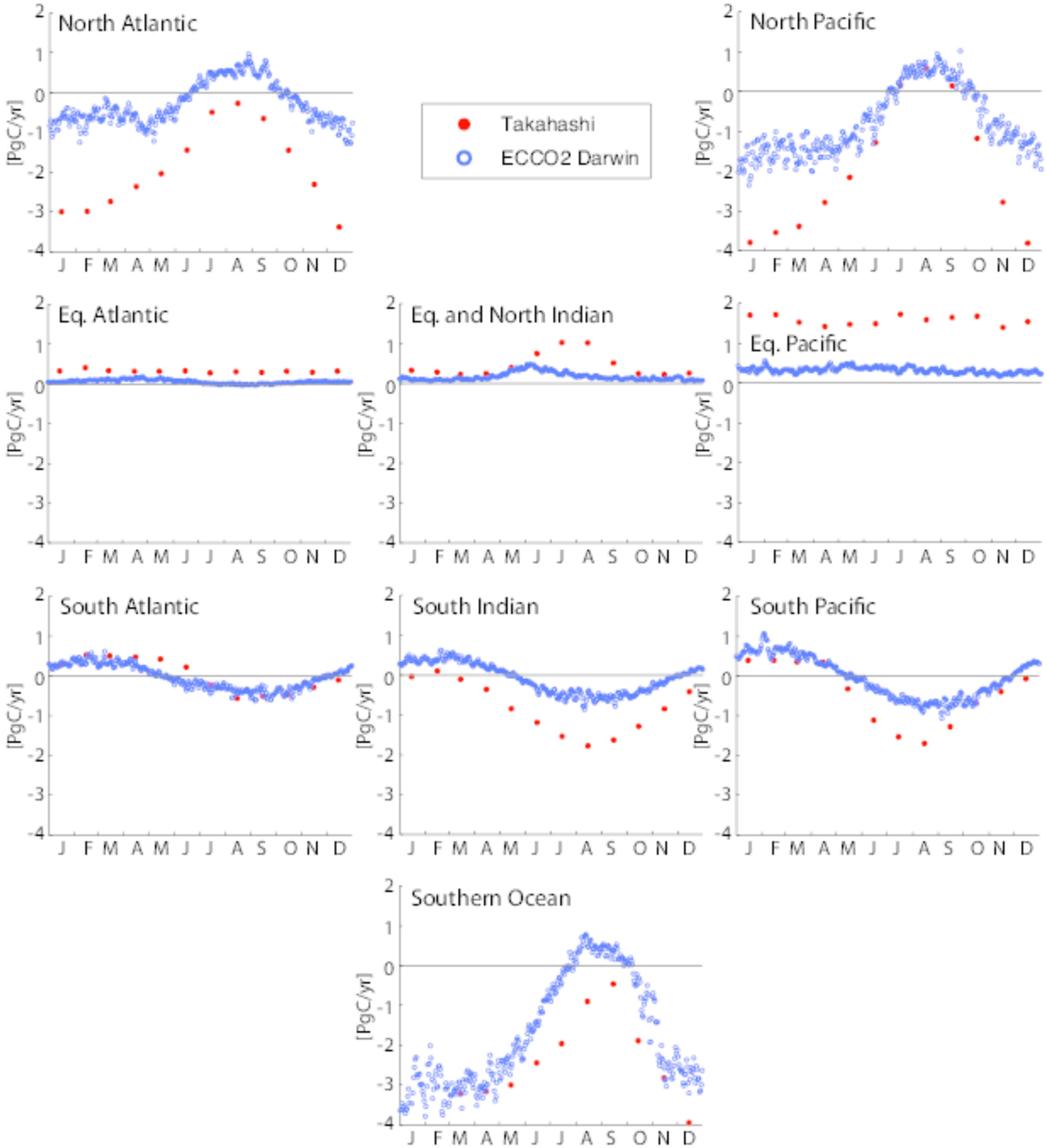
Simulated air-sea CO_2 fluxes (global integral)



Mean flux during 2009—2010 in PgC/yr:

NOBM IC:	-0.2
Takahashi:	-1.1
Version 2	-2.4
GLODAP:	-3.3
Version 1	-3.7

Simulated air-sea CO_2 fluxes



Annual mean CO_2 flux for 2010
Positive: upward

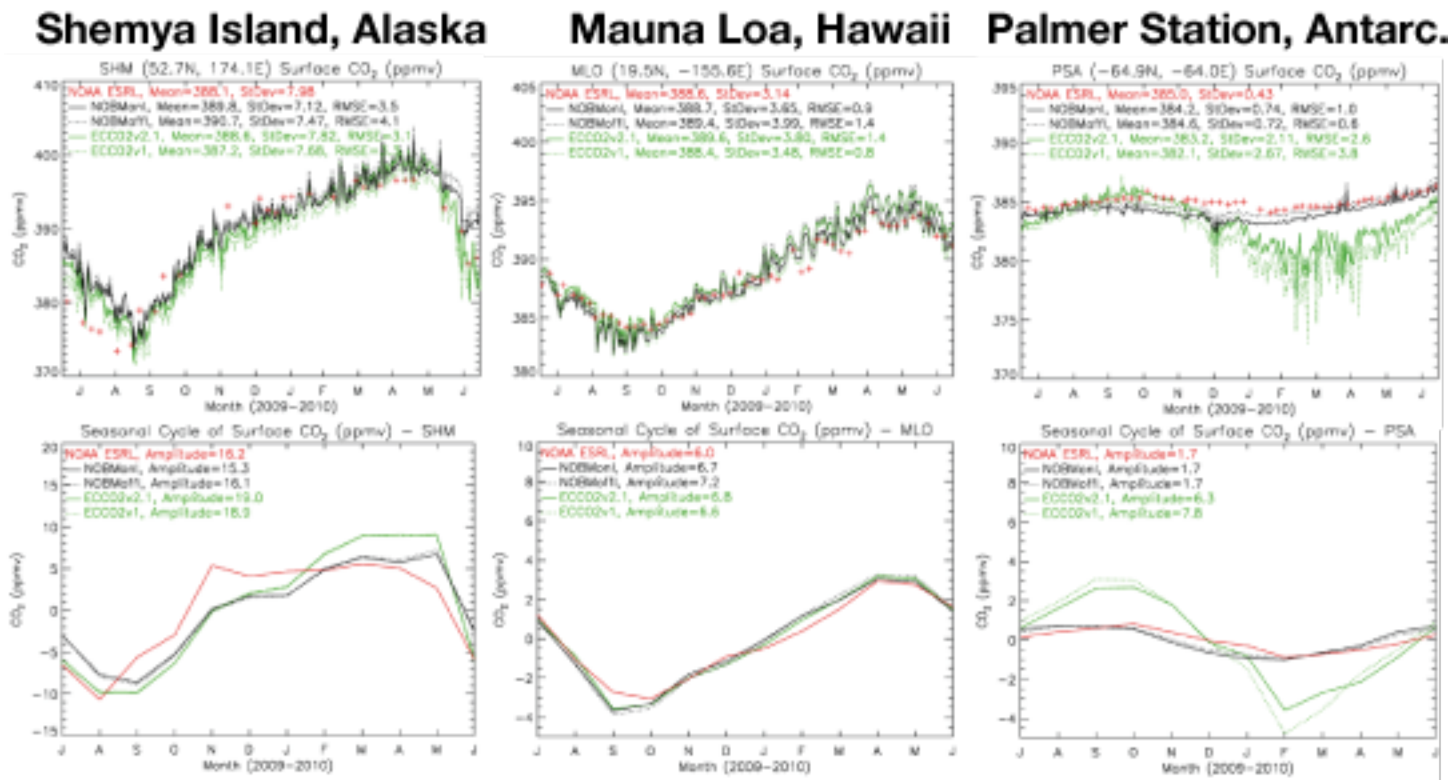
Takahashi (2000)
Optimized (2010)

Comparison with Observations

Seasonal Cycles of Atmospheric CO_2 Concentrations

Actual values

Detrended and filtered



NOAA ESRL data, GSFC's NOBM, ECCO2-Darwin

Graphs: Lesley Ott, GSFC

Summary and Planned Work

- Long spin-ups of high-resolution ocean biogeochemical models are problematic because of computational cost and model drift.
- This leads to unrealistic air-sea carbon flux estimates.
- A simple, physically-consistent data assimilation approach based on model Green's functions (forward sensitivity experiments) has been used to reduce model-data mismatch.
  - Using surface $p\mathrm{CO}_2$ data yielded modest flux improvements
  - Additional in-situ and satellite data constraints (DIC, alkalinity, ocean color) will improve flux product for CMS project
- Additional model improvements are needed to address regional biases